2011

Centralized wind power plant voltage control with optimal power flow algorithm

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by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Electrical Engineering

Program of Study Committee:
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Iowa State University

Ames, Iowa

2011

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Acknowledgements

There are several people who I would like to thank for their support in completing this project: The principals at P & E Engineering—D. Blasberg, T. Ernst, R. Kline, and A. Powers—for teaching me the practical art of power systems design and paying for a significant portion of my degree; A. Kline, R. Kline, Dr. Liu, and A. Powers for reviewing drafts of this thesis; Dr. Liu for agreeing to take on an off-campus student and his help with my research project; and Dr. Ajjarapu and Dr. Govindarasu for agreeing to fill out the remainder of my committee. Additionally, L. He and N. Acharya provided assistance with research. Dr. Aliprantis provided assistance with the understanding of Type 4 WTGs. Dr. McCalley also allowed use of lecture notes from previous semesters.

There are four people without whom I would likely have never gotten to this position. The first is my wife. It has been very difficult to sit down and spend time on my studies after long days at work, and her loving support and encouragement has proven very helpful, especially when I began work on the research and thesis almost two years ago. I would like to thank her for cooking and doing more than her share of housework while I watched lecture videos and worked on homework assignments and research.

I have been lucky to have two parents who truly value education. Dad is a Principal Engineer at P & E Engineering and also spent many years at the companies that became MidAmerican Energy. Mom is a GT Coordinator with Des Moines Public Schools and has spent the majority of her career as a classroom teacher. They both genuinely loved and are very good at their chosen professions. This has spilled over into the career choices of their children who have followed in their parent's footsteps. My brother, Dan, is in management at Xcel Energy in Minneapolis and spent several years as an engineer in transmission planning. My sister, Kelsey, is a Ph.D. candidate in musicology at Washington University in St. Louis and hopes to one day teach at the college level.

I have had several excellent teachers through the years, and none has been more influential than S. Waugh, my high school German teacher. While I was not a poor student in high school, I did not apply myself to my high school classwork as well as I could have. With his help and encouragement, I won the Congress-Bundestag scholarship that sent me to

Germany for a year as an exchange student. Without this experience, I doubt that I would have taken the first few years of college seriously enough to put in the extra hours that were necessary to excel. I would not be surprised to learn that my academic performance in high school was in the bottom half of the freshman engineering students with whom I started my career at Iowa State, but my performance as an undergraduate student was significantly better than average. While many people, including J. Otto, E. Pilartz, H. Prüßmann, and the Nagel and Wippenhohn families (especially P. Nagel and E. Wippenhohn) helped to make the experience a positive one, it would not have happened without Herr Waugh.

Abstract

This thesis presents a method of controlling the reactive power injected into a medium-voltage collection system by multiple wind turbine generators such that the voltage at one bus is maintained at a specified level. The proposed control accounts for the system impedance between the wind turbine generator terminals and the point of interconnect, and utilizes an optimal power flow algorithm to dispatch reactive power amongst the wind turbine generators. This optimal power flow algorithm minimizes real power losses within the wind power plant and avoids operating conditions that violate various operating constraints.

This thesis presents a 100 wind turbine generator wind plant test system and uses this test system to demonstrate the potential increased revenues occasioned by the proposed control system as compared to a system that dispatches the wind turbine generator reactive power injections uniformly. Analysis shows that it can be cost effective to install the proposed control system.

Chapter 1 Introduction

The rapid growth of the wind industry in the United States and elsewhere has forced large wind power plants (WPPs) to provide ancillary services more similar to what is expected of a traditional power plant. To meet this demand, wind turbine generator (WTG) manufacturers offer centralized control systems that can provide many of these services [1].

This thesis focuses on one of these ancillary services, voltage and/or reactive power control; however, the control proposed could be expanded to other ancillary services such as frequency regulation. Chapter 2 provides an introduction to the topology of large-scale wind power plants. The standard AC power flow equations are provided in Chapter 3 along with their implications for voltage control. A centralized voltage control algorithm is proposed in Chapter 4.

The remainder of the thesis focuses on the benefits of the proposed control system, namely the ability to minimize electrical losses within the WPP and the ability to avoid violating system constraints. Chapter 5 presents a test WPP system that is used in the case study discussed in Chapter 6 and attempts to estimate the reduction in collection system energy losses caused by the use of an optimal reactive power dispatch strategy. The results of the case study are discussed in Chapter 7.

In the remainder of this paper, equations enclosed in a box are direct quotes from the source named in text.

Chapter 2 Large-Scale Wind Plants and Wind Plant Collection Systems

Utility Scale WPPs

For the purposes of this paper, utility-scale WPPs consist of several wind turbines that are connected to the bulk transmission system at one point. The following is a general description of the utility scale WPPs that are presently being built in the United States. The IEEE PES Wind Plant Collector System Design Working Group has published several papers on the subject of collection system design including [1]–[9].

WTG Characteristics

In large-scale WPPs, the individual wind turbine generators (WTGs) typically have terminal voltages in the low-voltage spectrum. Figure 1 in [2] shows a turbine with a 575V turbine terminal voltage and Figure 1 in [3] states that terminal voltages between 400V and 690V are typical. The individual wind turbines are connected to a medium voltage collection system via a transformer [2]. This transformer may be a part of the turbine itself or a separate unit located outside the tower [3]. Where the transformer is located outside the WTG, it is typically a three-phase pad-mounted transformer similar to those utilized on utility distribution systems [2].

Medium-Voltage Collection System

The medium-voltage collection systems utilized in WPPs is discussed in [2] and [4]. Distribution class components in the 15kV, 25kV, and 35kV classes are widely available for both underground and overhead distribution systems. These components are defined by industry standards such as [10], [11], [12], and [13]. The use of higher voltages has several well-documented advantages, including reduced losses, ability to carry larger amounts of power over longer distances, and better voltage performance.

The typical medium voltage collection system at WPPs constructed in the United States is operated at 34.5kV [2]. While [2] does not justify the use of 34.5kV as the standard collection system voltage; it appears to be that this is the highest voltage class for which standard distribution system components, especially cable accessories such as splices, terminators, and elbows, are available is 35kV.

The use of standard medium-voltage components is typical of utility practices. Use of standard components minimizes inventory and increases familiarity of crews with correct installation practices reducing the probability of serious mistakes during installation [4]. Though not specifically discussed in [4], use of standard components reduces costs due to the widespread availability of the components (Reference [2] describes pad-mounted transformers as "commodities") and provides for some interchangeability between manufacturers. These standard utility practices have carried over to the wind industry and WPP medium voltage collection systems are typically constructed with standard distribution class components [4].

The medium-voltage collection systems can be overhead, but are more typically underground as they are more acceptable to landowners and can also result in reduced losses, higher reliability, and fewer restrictions on the movement of construction equipment. These collection circuits are typically constructed in a radial fashion with the turbines connected in a daisy chain, utilizing junction boxes and the loop-feed bushings in the turbine transformers [2].

In the author's experience, this radial configuration is significantly different than what is typical of modern underground residential distribution (URD) circuits. While practices vary between utilities, in a typical URD circuit the underground cable would be configured in a loop with a normally open point in the middle. This allows any individual cable segment to be de-energized and repaired while maintaining service to customers and allows service to customers to be restored prior to repairing a failed cable. This method reduces outage durations, but results in a higher installation cost. In a looped system, the cables will also necessarily be normally operated at significantly less than maximum capacity, significantly reducing losses.

Substation Characteristics

The medium voltage collection circuits terminate in a substation and are connected to the main substation bus via circuit breakers. These circuit breakers and main bus are typically an open bus design [6]. The alternative to an open bus design is metal-clad switchgear, which the author has also seen on recent projects.

Each collector circuit may be connected to a circuit breaker that is dedicated to that cable, or multiple cables may be combined and connected to one circuit breaker. The collection circuits are then connected to the bulk transmission system via transformers in the substation and a transmission line. This transmission line may amount to bus across a fence into an adjacent switchyard or may be several miles long, depending on the distance to the point of interconnect [2]. Depending on a variety of factors, the WPP substation may contain one or more transformers [9].

The substation may also contain reactive power compensation equipment [1].

Chapter 3 The Voltage Control Problem

Reactive power is commonly used to control voltages on power systems. The justification for using reactive power to control voltage is described in several standard power systems analysis textbooks and other resources, including [14] and [15].

The Power Flow Equations

One form of the power flow equations are given in (3.1) and (3.2), which are given as Equation (10.5) in [14] (p. 326) and Equations (25a) and (25b) in [15].

$P_i = \sum_{k=1}^{n} \lvert V_i \rvert \lvert V_k \rvert \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik} \right)$	(3.1)
$Q_i = \sum_{k=1}^{n} \lvert V_i \rvert \lvert V_k \rvert \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik} \right)$	(3.2)

Where:

- P_i is the net real power injection at bus i
- Q_i is the net reactive power injection at bus i
- $|V_i|$ is the magnitude of the voltage at bus i
- $|V_k|$ is the magnitude of the voltage at bus k
- G_{ik} is the real component of the entry at position i, k of the bus admittance matrix Y_{BUS} [15]
- B_{ik} is the imaginary component of the entry at position i, k of the bus admittance matrix Y_{BUS} [15]
- θ_{ik} is the angular difference between the complex voltages of buses i and k

Decoupling of Active and Reactive Power

The decoupling of active and reactive power is discussed in [14] and briefly in [17]. In [14], the decoupling of active and reactive power is demonstrated by developing the power flow problem, the Newton-Raphson solution algorithm, and the Jacobian. Here, a less rigorous approach is utilized to arrive at the same conclusion.

To demonstrate the decoupling of active (real) and reactive power, take the partial derivative of (3.1) and (3.2) with respect to θ_k and V_k. This yields (3.3), (3.4), (3.5), and (3.6) which are given as Equation (10.40) in [14] (p. 345) and (9), (11), (13), and (15) in [16] (p. 10) with the $_p$ and $_q$ subscripts replaced with $_i$ and $_k$, respectively.

$\frac{\partial P_i}{\partial \theta_k} = \lvert V_i \rvert \lvert V_k \rvert \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik} \right)$	(3.3)
$\frac{\partial P_i}{\partial V_k} = \lvert V_i \rvert \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik} \right)$	(3.4)
$\frac{\partial Q_i}{\partial \theta_k} = -\lvert V_i \rvert \lvert V_k \rvert \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik} \right)$	(3.5)
$\frac{\partial Q_i}{\partial V_k} = \lvert V_i \rvert \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik} \right)$	(3.6)

In typical overhead transmission systems, the resistance and θ_{ik} will be relatively low [14]. Additionally, voltages will be close to 1.0 pu under most operating conditions.

Assume:

$$\theta_{ik} \approx 0$$

$$V_i \approx 1$$

$$V_k \approx 1$$

$$G_{ik} \approx 0$$

Substituting these into (3.3), (3.4), (3.5), and (3.6) yields (3.7), (3.8), (3.9), and (3.10).

$$\frac{\partial P_i}{\partial \theta_k} \approx -B_{ik} \tag{3.7}$$

$$\frac{\partial P_i}{\partial V_k} \approx 0 \tag{3.8}$$

$$\frac{\partial Q_i}{\partial \theta_k} \approx 0 \tag{3.9}$$

$$\frac{\partial Q_i}{\partial V_k} \approx -B_{ik} \tag{3.10}$$

Equation (3.8) implies that an incremental change in real power injection at a particular bus has relatively little impact on bus voltage at neighboring buses. Similarly, (3.9) implies that an incremental change in the reactive power injection at a particular bus will have relatively limited impact on the angular difference across the branches connected to that bus.

Equation (3.7) implies that an incremental change in the real power injection at a particular bus will have a relatively large impact on the angular difference across the branches connected to that bus. Similarly, (3.10) implies that an incremental change in the reactive power injection at a particular bus will have a relatively large impact on voltage at neighboring buses.

Stated differently, real and reactive power control different properties. On a steady-state basis, changes to the real power injections can best control the angular difference across a branch. Similarly, changes to the reactive power injections control bus voltages [14].

Chapter 4 Optimal VAR Flow Voltage Control for Large Scale Wind Power Plant

Introduction

The wind industry in the United States has grown rapidly over the past several years. Installed wind capacity in the United States totaled 40 181 MW at the end of 2010. Of these, 5 116 MW were added in 2010 [18]. The growth of the wind industry has forced large wind plants to provide ancillary services similar to those provided by conventional generation facilities. In order to provide these ancillary services, wind turbine generator (WTG) manufacturers offer centralized control systems [1].

Large-Scale Wind Plants and Wind Plant Collection Systems

For the purposes of this paper, large utility-scale wind power plants (WPPs) consist of several WTGs that are connected to the bulk transmission system at one point. References [1] through [9] were prepared by the IEEE PES Wind Plant Collector System Design Working Group and describe the general topology and design considerations of the wind plants currently being constructed in the United States.

Medium-Voltage Collection System

The individual WTGs utilized on recent utility scale projects in North America tend to have nameplate generation capabilities between 1.5 and 2.5 MW. The WTGs in use on utility scale WPPs generally have terminal voltages between 400V and 690V [3]. In the author's experience, 690V is a very common terminal voltage. The individual WTGs are connected to a medium-voltage collection system through a transformer located within or next to the WTG [3]. If the transformer is located outside of the WTG, the transformer is likely to be very similar to the three-phase pad-mounted transformers utilized on utility distribution systems. The medium-voltage collection systems are typically operated with a nominal voltage of 34.5kV [2].

The medium-voltage collection system connects the individual WTGs with a substation that contains a transformer connecting the medium-voltage collection system with the bulk transmission system. The medium-voltage collection system is normally constructed in a radial topology with underground cables, though overhead collection systems have also been constructed [2].

The Voltage Control Problem

Reactive power is commonly used to control voltages on power systems. The justification for using reactive power to control voltage is described in several standard power systems analysis textbooks including [14]. In typical overhead transmission systems, the resistance will be small compared to the reactance. On a steady state basis, the result of this is that bus voltages are best controlled by changing the reactive power injections while the difference in voltage angle between buses is best controlled by changing the real power injections [14].

Reactive Power Compensation

A large wind plant can consist of many WTGs, which may have reactive power capability, and the WPP may possess substation reactive power resources such as switched capacitors and reactors or dynamic devices such as static VAR compensators [1]. There have been several papers discussing the use of wind plants for the control or support of voltages on the bulk transmission system including [19] and [20] and discussion of the WTG characteristics, including reactive power capability, particularly the doubly fed induction generators (DFIG) including [5], [19], and [21]. Reference [22] proposes a transient model of the DFIG for use in transmission system level studies.

Reference [1] discusses the requirements and design methodology for WPP reactive power compensation systems in the United States subject to regulation by FERC. This paragraph is a summary of this discussion. The interconnecting utility (transmission provider) performs a system impact study as a part of the interconnection process. FERC Order 661-A [23] allows the interconnecting utility to require the WPP to supply reactive power sufficient to provide a power factor between 0.95 leading and 0.95 lagging if the system impact study shows that it is necessary to maintain system reliability. This reactive power requirement typically applies to the complex power flow at the point of interconnect. The Large Generator Interconnection Agreement lays out other reactive power requirements that the WPP is expected to meet. The WPP is required to install sufficient reactive power resources (either WTGs with reactive power capability, substation resources, or a combination of the two) to meet this power factor requirement. If needed for reliability reasons, the interconnecting utility may also require that the reactive power resources be "dynamic" to provide continuous smooth control of the interconnect bus voltage. The WPP may be required to meet the reactive power requirement may be at one specific voltage, or over a range of voltages [1]. While not discussed in [1], reactive power requirements in the ERCOT region are different [24].

WTG Reactive Power Capability

The reactive power capabilities of the common WTG designs are discussed in [5]. References [19] and [21] also provide discussion of the capabilities of Type 3 (DFIG) WTGs. Type 1 and 2 designs (induction generators) are generally not capable of providing reactive power compensation, and the machines themselves actually absorb reactive power. Manufacturers of Type 1 and 2 designs normally provide several stages of switched power factor correction capacitors. Type 3 and 4 (full converter) WTGS are capable of operating as dynamic reactive power resources and may also be capable of generating reactive power when the WTG is not producing real power. The capability of Type 4 WTGs may vary with terminal voltage [5].

Substation Reactive Power Resources

If the WTGs do not have sufficient capability to meet the interconnect requirements described above, reactive power resources must be provided in the substation. These resources may include switched capacitors and reactors, static VAR compensators (SVC), or static synchronous compensators (STATCOM). STATCOMs and SVCs can operate as dynamic resources, but are more expensive than fixed capacitors and reactors. If the transmission provider requires that the plant be capable of providing smooth voltage control, a combination of DFIG WTGs and switched capacitors and reactors may be acceptable [1].

Reference [1] also discusses low-voltage ride-through requirements and the role that power factor compensation has in low-voltage ride-through requirements.

Collection System Losses

Energy that is generated by the WTGs but not delivered to the point of interconnect reduces the operator's potential profits [9]. The analysis of losses in the WPP is discussed in detail in [6]. Additionally, losses in specific pieces of equipment are discussed in [4] and [9]. Energy can be lost through electrical resistance in the system and no load losses in transformers. Furthermore, energy that is not generated due to equipment failures within the WPP should also be considered as a portion of system losses. A thorough collection system design will be based on total life-cycle cost. This analysis will determine if the incremental savings in losses occasioned by a design change offset the cost of that design change [6].

In addition to their consideration during the design phase, losses should be a consideration during the operation of the WPP as well [25], [26].

Wind Plant Control

Centralized Control Systems

Reference [1] alludes to centralized control systems that can provide ancillary services that are required by transmission providers. Reference [27] describes the features that are available with the control systems from one manufacturer. In addition to other features, these control systems can monitor voltage and current at the substation and adjust the reactive various power resources (including the WTGs) to meet a desired voltage set point.

The remainder of this paper assumes that the wind plants will typically regulate voltage at a specified point in the system. There are several means of allocating the reactive power that is injected by the turbines amongst the several turbines. The simplest would be to divide the total amount to be supplied equally amongst the WTGs. References [28], [29], and [30] propose methods of dispatching reactive power proportionally amongst the individual WTGs based on the relative reactive power capability of each WTG. This has the advantage of maintaining an equal margin between the turbine operating point and the maximum possible injection [28]. Reference [31] provides a method for using a central proportional integral control to regulate the reactive power flow at the point of interconnect, but provides each WTG with the same power factor signal. The methods presented in [28], [29], [30], and [31] have the advantage of being relatively simple to implement but appear to ignore the differences in impedance between the WTG terminals and the point of interconnect across the WPP.

Reference [32] proposes a method dispatching reactive power in a large WPP that regulates voltage at a pre-determined location and considers the impedance of the collection system in allocating reactive power amongst the WTGs.

Other papers also present methods of dispatching reactive power but focus mostly on low voltage ride through. These include [33] and [34].

References [25] and [26] propose dispatching reactive power in an offshore WPP utilizing a particle swarm optimization method. The WPP referenced in these papers is connected to the mainland 400kV transmission system via submarine 150kV AC power cables. While these papers develop the general OPF problem that is broadly applicable to many WPPs with AC collection systems, and advocate use of an OPF algorithm to dispatch reactive power during the planning and operations stage, they do not extend the concept to the development of the reactive power dispatch to a controller that is intended for use in an on-line environment to regulate voltage at a specific bus.

Reference [35] presents a centralized control scheme that dispatches reactive power amongst the WTGs using an optimal power flow algorithm. Though [35] briefly discusses using the WPP to control interconnect bus voltage, the proposed control system receives the desired reactive power injection from the transmission operator. The control system appears to be open loop and does not contain a feedback loop to regulate the WPP reactive power injection to the desired level.

This paper presents an optimal control system similar to [25], [26], and [35] but applied to the large-scale WPPs currently being constructed in the United States. The control system contains a feedback loop and is capable of being used in an on-line environment to regulate voltage to a predetermined set-point.

Proposed Approach

The approach proposed in this paper is to allocate the reactive power amongst the WTGs and substation resources using an AC optimal power flow algorithm. This has the advantage of minimizing losses and can also incorporate the substation VAR resources.

Optimal Power Flow

Optimal power flow is an extension of the economic dispatch problem in which the constraints include the set of power flow equations describing the transmission system. In the classic optimal power flow problem, the generation dispatch of a power system is determined so as to find the dispatch that will satisfy the system load at the lowest cost. It is also possible to minimize losses in the system or the amount of load to be shed [36].

By including constraints such as minimum and maximum bus potentials, branch currents, and generator real and reactive power injections, the optimal power flow solution can be forced to realize the various constraints on the operation of the system. Some of the possible control variables include generator real power injection and terminal voltage, transformer load tap changer (LTC) position (where present), and capacitor switch status. The system model would need to include the loads at each bus, branch impedances, generator incremental cost data and constraints. Constraints on the solution would typically include transmission line flows, bus voltages, and generator minimum and maximum real and reactive power injections [36].

Application to Wind Plant Collection Systems

In the operation of the in-plant electrical system of a WPP, the problem is substantially different. The objective of site operation is obviously to maximize profits which are determined by the real power delivered to the transmission system at the point of interconnect and therefore requires the minimization of losses within the WPP. Under normal operating conditions, the WTG real power injections are determined by the wind prevailing at each WTG. The only way to maximize the real power delivered to the point of interconnect is to minimize the real power losses within the site. Because the ability to control generator real power injections has been taken away, the only means to reduce system losses is to change the reactive power dispatch. As described above, the WPP is often required to regulate voltage at a predetermined bus to a specific level. This serves as a further constraint on the reactive power dispatch.

In the case of a WPP, the control variables include the WTG reactive power injection (assuming that the turbines have means of varying the reactive power injection), and may include the transformer LTC tap position (the substation transformers are often not supplied with load tap changers and [9] recommends avoiding them), switched capacitor status, and the reactive power injection from a static VAR compensation system. The system model would need to include all branch impedances including cables, overhead lines, and transformers. The transformers and medium-voltage cable systems are generally designed to carry the maximum expected load, thus thermal constraints are typically not a limiting condition. Constraints include bus voltages, generator minimum and maximum reactive power injection, and, if applicable, maximum and minimum transformer LTC position.

The discussion of the optimal power flow problem provided in the paragraphs above is consistent with [25], [26], and [35], except that load tap changers appear to be common in the systems described in [25] and [26].

Proposed Control Topology

The proposed control system will regulate the voltage or reactive power flow at a designated point in the system (usually the point of interconnect) to a predetermined value while dispatching the reactive power amongst multiple wind turbines so as to minimize total system losses. The inputs and outputs of the proposed control are listed below. This generally agrees with the formulations provided in [25], [26], and [35].

Control Inputs

- System data (branch impedances, branch shunt admittances, transformer taps, etc.)
- Status of substation reactive power resources
- Limitations on changes to substation reactive resources
- Equipment thermal limitations

- Bus voltage limitations
- WTG real power injections
- Voltage set point and regulated bus
- WTG reactive power capabilities
- Real power production at each WTG

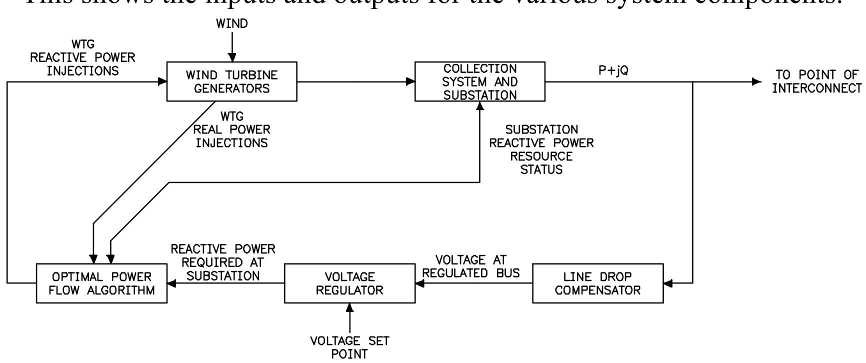
Control Outputs

- Reactive power injected by each WTG
- Changes to status of substation reactive power resources

Methodology

Because the amount of reactive power that needs to be injected into the transmission system to achieve the desired voltage set point is not known, a feedback control mechanism is required to regulate the voltage to the desired set point. This feedback control compares the error between the between the measured voltage at the point of interconnect to the voltage set point and adjusts the reactive power generated by the wind plant to reduce the error. A block diagram of this control scheme is shown in Figure 4-1.

Figure 4-1: Wind plant voltage control.
This shows the inputs and outputs for the various system components.



In this case, the control system monitors the voltage and current at a point in the substation. This information is fed into a line drop compensator that calculates the voltage and real and reactive power injections to reflect those present at the regulated bus. The system described in [27] is capable of regulating the voltage at a remote bus. As noted in [1] this is often the point of interconnect. If several plants are located in close proximity, it may be necessary to regulate a different bus or even a fictitious point within the plant. This has the effect of creating "voltage droop" and allows the plants to share voltage regulation duties [37]. The calculated voltage at the regulated bus is fed into the voltage regulator which compares the measured voltage with the voltage set point and calculates the reactive power that the OPF should deliver to the substation in order to produce the desired voltage.

In order to solve the OPF, the algorithm will also need the real power injected by each WTG, the voltage limits at each bus, and the current or MVA limits in each branch. It is assumed that under normal conditions the real power injected by each WTG will be determined by prevailing wind conditions and the WTG real power injections would be equality constraints. If generation is curtailed due to transmission constraints or the wind plant is providing frequency regulation, this would not be the case. The OPF also needs to know the status of the substation VAR resources. For switched shunt devices such as capacitors and reactors, the number of times that the devices are switched should be limited to avoid excessive wear and to reduce circuit breaker or circuit switcher maintenance costs. Additionally, a delay must be built in to prevent reenergizing a capacitor until the voltage across the capacitor has decayed to a point where the energizing transients will be acceptable [38]. The optimal power flow problem is developed below.

$$\min P_{loss} = \sum_{ik=1}^{n} |I_{ik}|^2 R_{ik} \tag{4.1}$$

For all n branches

Subject to:

$P_i = \sum_{k=1}^{n} \lvert V_i \rvert \lvert V_k \rvert \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik} \right)$	(4.2)
$Q_i = \sum_{k=1}^{n} \lvert V_i \rvert \lvert V_k \rvert \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik} \right)$	(4.3)

$$P_{Gi} = P_{WINDi} \tag{4.4}$$

$$|V_{POI}| = |V_{SETPOINT}| \tag{4.5}$$

$$Q_{POI} = Q_{VREG} \tag{4.6}$$

$$Q_{MINWTGi} \leq Q_{WTGi} \leq Q_{MAXWTGi} \tag{4.7}$$

$$|V_{MINi}| \leq |V_k| \leq |V_{MAXi}| \tag{4.8}$$

$$|S_{ik}| \leq |S_{MAXik}| \tag{4.9}$$

Where:

- P_{Gi} is the real power injected at bus i
- P_{WINDi} is the real power that the WTG at bus i is capable of injecting based on prevailing wind conditions
- Q_{POI} is the reactive power supplied to the point of interconnect
- Q_{VREG} is the reactive power demanded by the voltage regulator
- $|V_{POI}|$ is the voltage magnitude at the point of interconnect (or other regulated bus)
- $|V_{SETPOINT}|$ is the scheduled voltage at the point of interconnect
- $Q_{MINWTGi}$ is the maximum reactive power that the WTG at bus i can absorb
- Q_{WTGi} is the reactive power supplied by the WTG at bus i
- $Q_{MAXWTGi}$ is the maximum reactive power that the WTG at bus i can supply
- $|V_{MINi}|$ is the minimum voltage magnitude each bus i
- $|V_i|$ is the voltage magnitude at bus i
- $|V_{MAXi}|$ is the maximum voltage magnitude at bus i
- $|S_{ik}|$ is the apparent power flowing in branch ik
- $|S_{MAXik}|$ is the maximum apparent power flow in branch ik
- $|I_{ik}|$ is the current magnitude flowing in branch ik
- R_{ik} is the positive sequence AC resistance in branch ik
- G_{ik} and B_{ik} are the real and imaginary components of the bus admittance matrix

Note that (4.2) and (4.3) are given as Equation (10.5) in [14] (p. 326). The formulation of the optimal power flow problem given in (4.1)–(4.9) is consistent with the formulation provided in [25], [26], and [35].

Voltage Regulator

There are numerous possible topologies that would be suitable for the voltage regulator. Proportional integral derivative (PID) controllers are commonly used in industry for a variety of functions [39]. The author sees no reason why they could not be adapted to this purpose. A transfer function for a standard PID controller is provided in Equation (12.57) in [39] (p. 601), which is repeated in (4.10) below.

$$G_{PID}^{app}(s) = K_P + K_i \frac{1}{s} + K_d \frac{s}{\tau s + 1} \qquad (4.10)$$

The constants K_p, K_i, and K_d are selected based on desired control response [39].

Practical Considerations

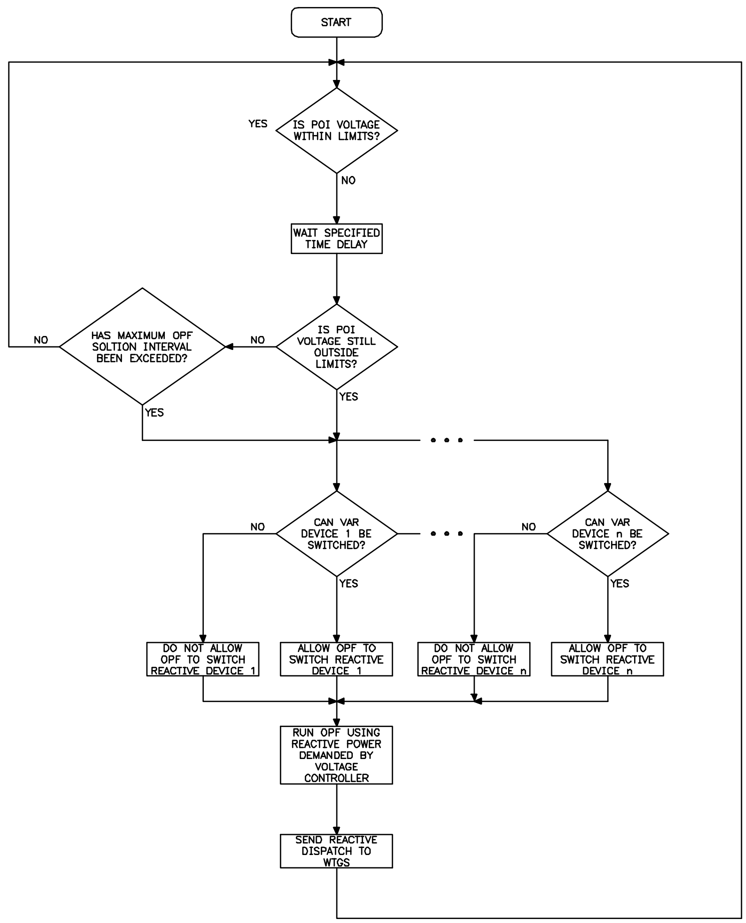
Dead Band and Coarse Control

A dead band would likely be implemented as a part of the voltage regulator. This would mean that the control system would solve the OPF only after the measured voltage deviated from the set point by more than a predetermined amount for a specified duration. The width of the dead band would be based on discussions with the transmission provider and the delay would be long enough that the control would not act for faults or other temporary conditions. This would serve to reduce the computational requirements while still ensuring that voltage is adequately regulated. Additionally, it would likely be desirable to solve the OPF at regular intervals or after large changes in real power to ensure that the reactive power resources are still dispatched optimally. A flow chart showing the logic that will initiate an OPF solution is provided in Figure 4-2.

Fine Control

This dead band will cause the control system to provide a relatively coarse regulation of the desired set point. Two possibilities exist if fine voltage control is necessary. The first possibility is to use dynamic substation reactive power resources such as static VAR compensators. The alternative is to adjust the WTG reactive power injections as necessary using linear sensitivity analysis of the OPF results.

Figure 4-2: OPF flow chart.
This shows the logic used in executing the OPF.



Linear sensitivity analysis is discussed briefly in [40] in the context of linearizing the power flow equations. This method utilizes partial derivatives to show the variation in one quantity when another quantity is changed. This method is only useful for small deviations from the original power flow solution. This is especially true in cases where the sensitivity factor is for voltage or reactive power flow [40].

In this case, the OPF solution is linearized. One sensitivity coefficient is calculated for each WTG and shows the change in reactive power injection at the WTG for a change in reactive power delivered to the point of interconnect. An inelegant way of approximating the linear sensitivity coefficients is to solve the OPF twice, once with the reactive power demanded by the voltage controller, and the second with a small incremental change. The linear sensitivity coefficients are then calculated by comparing the reactive power dispatches from the two OPF solutions.

The linear sensitivity coefficient for WTG i, δQ_{WTGi}, is defined in (4.11). This provides the sensitivity of the reactive power injected by WTG i to changes in reactive power provided to the bulk transmission system at the point of interconnect.

$$\delta Q_{WTGi} = \frac{\partial Q_{WTGi}}{\partial Q_{POI}} \approx \frac{\Delta Q_{WTGi}}{\Delta Q_{POI}} \tag{4.11}$$

Where:

- Q_{WTGi} is the reactive power injected by WTG i
- Q_{POI} is the reactive power injected at the point of interconnect

Define ΔQ_{POI} as the change in power delivered to the bulk transmission system using (4.12).

$$\Delta Q_{POI} = Q_{NEWPOI} - Q_{POI} \tag{4.12}$$

Where:

- Q_{NEWPOI} is the new reactive power delivered to the bulk transmission system at the point of interconnect
- Q_{POI} is the reactive power delivered to the point of interconnect in the OPF solution

Next define the change in reactive power generation at WTG i, ΔQ_{WTGi}, using (4.13).

$$\Delta Q_{WTGi} = \delta_{WTGi} \bullet \Delta Q_{POI} \tag{4.13}$$

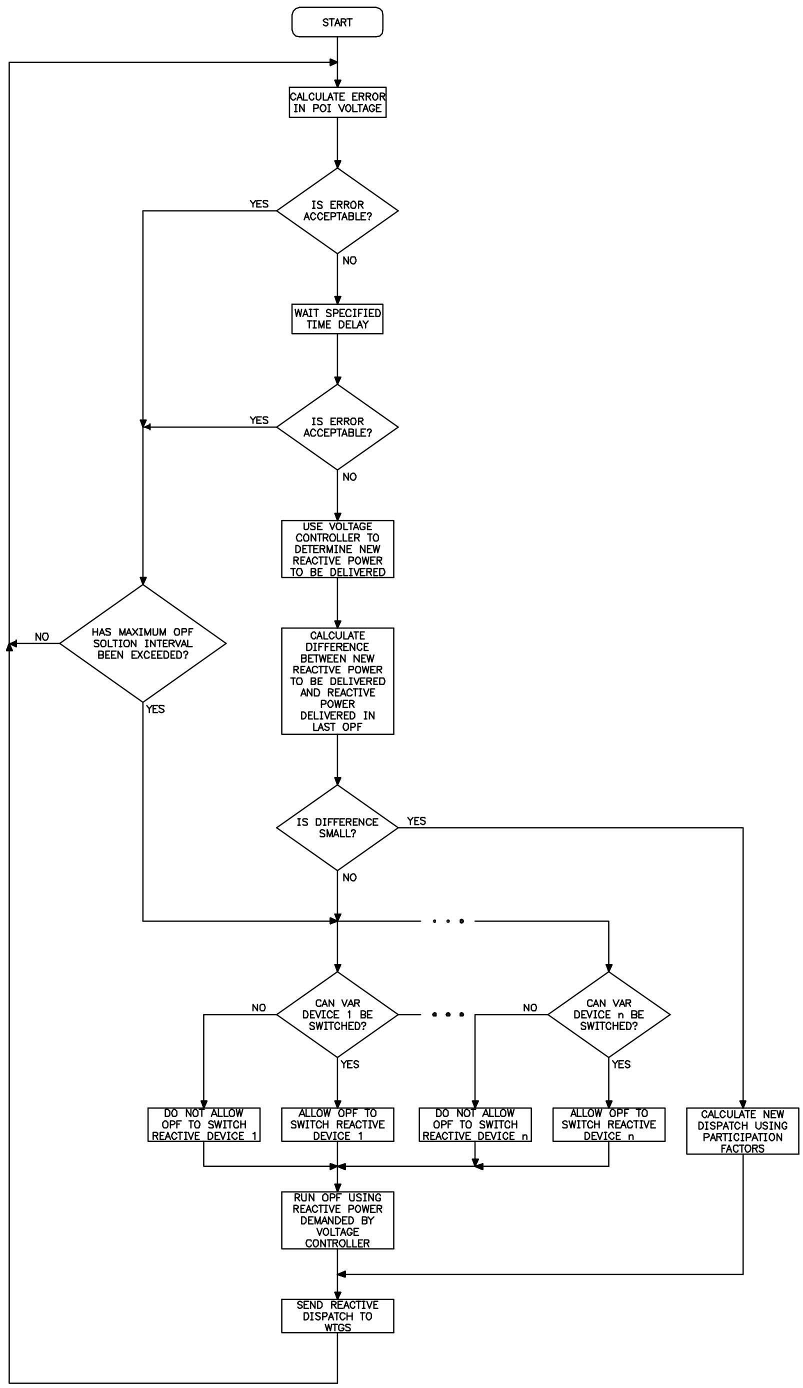
Next define the new reactive power generation at WTG i, $Q_{NEWWTGi}$, using (4.14).

$$Q_{NEWWTGi} = Q_{POI} + \Delta Q_{POI} \tag{4.14}$$

Where Q_{POI} is the reactive power injection at WTG i from the OPF solution.

It is possible that changing the reactive power injections in this manner may cause the bus voltages at one or more buses to violate constraints. The fine control should be used for relatively small adjustments that have negligible impact on voltage constraints. The difference between the actual reactive power being delivered to the point of interconnect and the value used in the last OPF solution would be used as a trigger to run a new OPF solution. This logic is shown in Figure 4-3.

Figure 4-3: OPF flow chart with additional logic to allow fine control.



Operation at Extreme Voltages or Reactive Power Injections

It is also important to note that the OPF algorithm will fail to return a feasible solution if it is unable to deliver the desired reactive power without violating constraints. This can be handled in two ways. The first is to limit the amount of reactive power that the voltage regulator can demand. The disadvantage to this is that the maximum reactive power that the WPP can deliver (or absorb) is dependent on the voltage at the point of interconnect. As an example, analysis shows that in situations where the WPP substation transformer is not equipped with a load tap changer, the POI bus voltage is high, and the WPP is being asked to supply large amounts of reactive power, the voltages at the electrically remote WTG buses will reach high levels and the remote WTGs may begin to absorb reactive power. This keeps the bus voltage at that WTG within limits, but reduces the reactive power that can be delivered and increases losses. At moderate voltage levels this is unlikely to happen unless the collection circuits are very long. See Chapter 7 for more discussion of this issue.

Another option is to implement logic that executes the OPF again if it fails. For the second attempt, the algorithm would be reconfigured so that it maximizes the reactive power that the WPP absorbs or delivers to the transmission system without reducing the real power generated by the WTGs. This would likely result in increased losses, but would allow for the WPP's full reactive power capacity to be utilized without exceeding equipment limitations. This would transform (4.1) into (4.15) or (4.16) below. All constraints remain identical to those above, which have not been repeated for brevity.

$$\max Q_{POI} \tag{4.15}$$

or:

$$\min Q_{POI} \tag{4.16}$$

Where Q_{POI} is the reactive power injected into the transmission system at the point of interconnect.

Physical Implementation

The centralized control proposed in this article would be located at the WPP. The control can be located in the substation control building or, alternatively, in the WPP operations building with transducers or metering equipment located in the substation control building measuring the voltage, current, and real and reactive power. The WPP SCADA system would provide these measurements to the control system. In the author's experience, fiber optic communications networks are typically built alongside the medium-voltage collection systems at large-scale WPPs. These fiber optic networks connect the WTGs with the plant SCADA system and can be used to communicate the reactive power dispatch to the individual WTGs. The local controllers at the individual WTGs would then be responsible for making adjustments to produce the desired level of reactive power.

The transmission provider can provide the voltage set point in a number of ways. In many cases, the transmission provider already has an existing SCADA connection with the WPP. The voltage set point can be provided via this SCADA link. Otherwise, voltage schedules can be provided in advance and entered into the SCADA system by WPP personnel.

As the majority of the SCADA equipment necessary to implement the control is already present in the majority of cases, the additional cost to implement this control would be largely limited to the cost of implementing the OPF software and the servers necessary to handle the extra computing load.

Conclusion

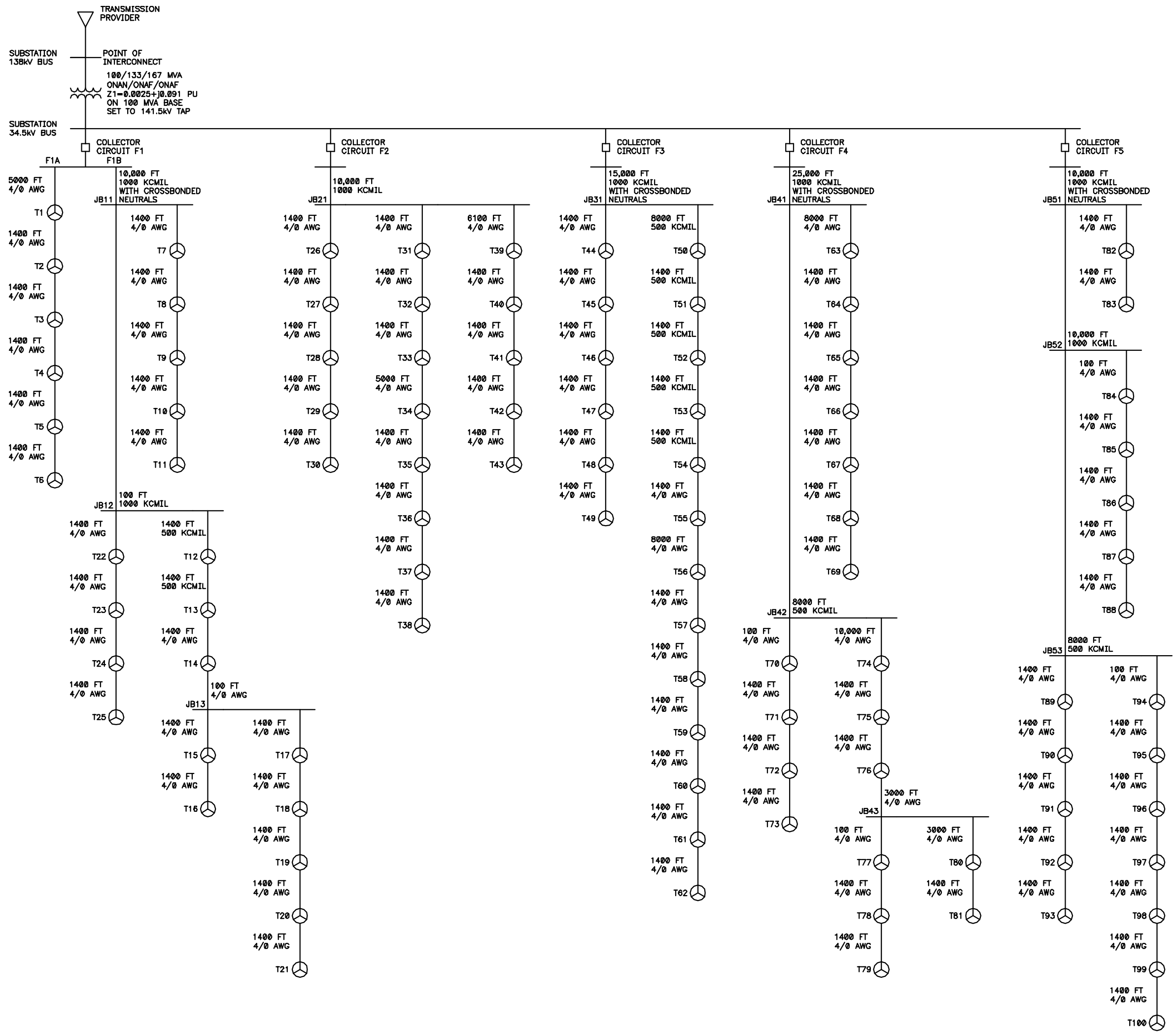
The control system described in this paper presents a method of distributing reactive power amongst the WTGs and other reactive power resources that minimizes system losses while regulating voltage at one point in the system. It is also capable of integrating voltage constraints that exist on the WPP collection system and avoiding operating conditions that violate these constraints.

There are several opportunities for further work. Perhaps the most obvious is the integration of such a reactive power dispatch scheme into a commercial WPP control system. Reference [27] discusses several ancillary services that commercial WPP control systems are capable of providing. These include frequency response and generation curtailment. Frequency response and generation curtailment necessarily require reducing the real power generation below the level that the prevailing wind is capable of producing, this is especially true if the WPP is expected to respond to under-frequency events [27]. The optimal reactive power dispatch could be extended to the real power dispatch under conditions when the real power generation is curtailed so that the WPP can respond to under-frequency events.

Chapter 5 100 WTG Test System Utilized for Case Study

Test System Model

Figure 5-1: Test collection system one-line diagram.

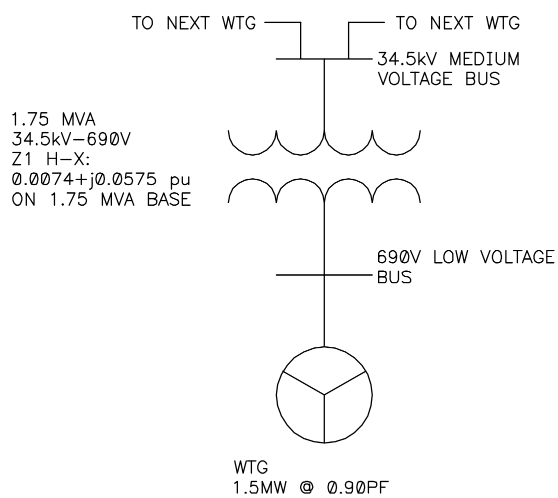


A 100-1.5 MW (150 MW total) WTG test system model was created using the MATPOWER software package. The MATPOWER AC OPF function utilizes a primal-dual interior point algorithm by default [41]. The software package also has a standard AC load flow algorithm. This model uses data that the author believes to be typical of WPPs currently under construction in the United States. The model assumes 1.5 MW WTGs with nominal terminal voltages of 690V. The WTGs are connected to an underground 34.5kV collection system using pad-mounted transformers. The 34.5kV collection system feeds into a substation with five 38kV circuit breakers. This substation is connected to a 138kV bulk transmission system via a transformer. The use of 1.5 MW WTGs with a terminal voltage of 690V is consistent with [42]. The use of pad-mounted transformers at each WTG is consistent with [2]. The use of a 34.5kV medium voltage collection system is consistent with [2]. In many parts of the United States, 138kV is a common bulk transmission voltage [43].

The system impedances are discussed in the paragraphs that follow. This model is positive sequence only, as the intention is only to run balanced three-phase load flow and OPF simulations. A one-line diagram of the system is shown in Figure 5-1. The discussion of system grounding, while interesting and important, is outside of the scope of this paper.

Due to space limitations, the WTGs are simplified in Figure 5-1. Each WTG is assumed to have the basic layout shown in Figure 5-2.

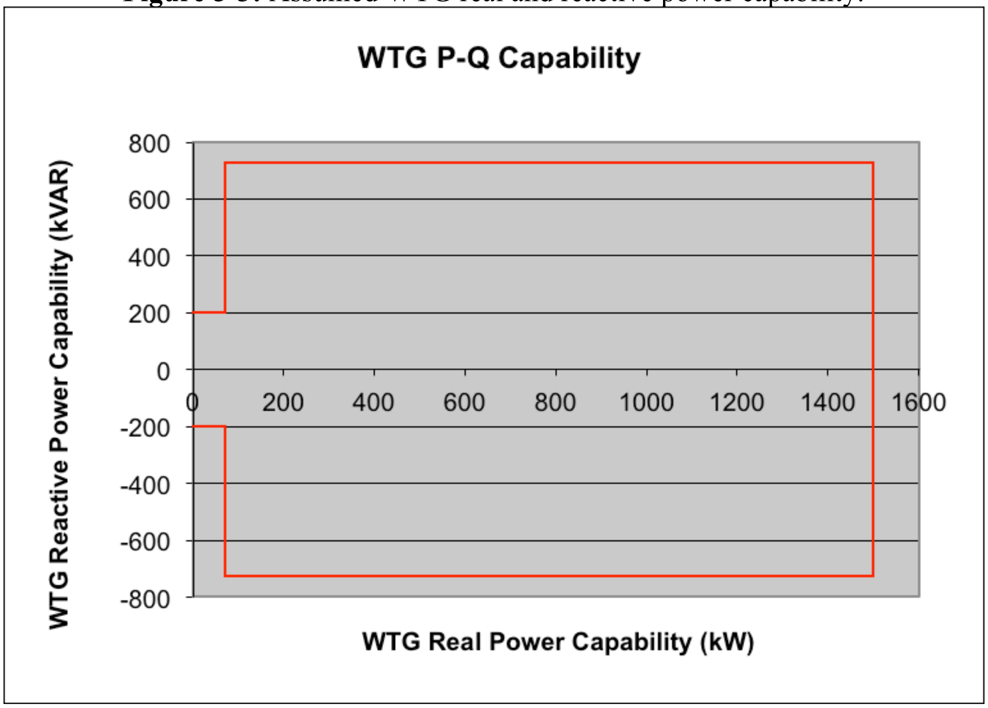
Figure 5-2: WTG configuration.
The WTG connects to the medium-voltage collection system through a transformer.
Note the loop feed bushings allowing convenient daisy chaining of WTGs.



WTG Data

The WTGs are assumed to be 1.5 MW Type 3 doubly fed induction generators (DFIG). Each is assumed to be capable of supplying or absorbing 726kVAR from minimum to full generation. It is assumed that when the WTG is not generating real power, it will be capable of producing or absorbing 200kVAR as described in [42]. This is shown in Figure 5-3. It is important to note that several references including [19] and [21] show that the reactive power capability of Type 3 (DFIG) WTGs increases as real power generation decreases. The assumed reactive power capability used in the case study is shown in Figure 5-3. This curve is believed to be the best representation of the data provided in [42].

Figure 5-3: Assumed WTG real and reactive power capability.



Turbine Transformer Data

The turbine transformers are 1750kVA ONAN units with an impedance of 0.74+j5.74%. This is typical of units supplied for a recent WPP project that the author was involved in and yields a nominal impedance of approximately 5.75% that is the standard for pad-mounted transformers with nameplate ratings between 750kVA and 2500kVA defined in [44] and described in [42] as typical. The X/R ratio is similar to the 7.5 that [42] describes as typical. No load losses for each unit are assumed to be 2kW and 4kVAR. It is assumed that the transformers would be set at nominal tap position.

For the purposes of this study, it is assumed that all transformers would have equal impedance. Reference [45] allows the impedance of identical units purchased at the same time to differ by up to 7.5% of the quoted transformer impedance.

35kV Cable

The test system utilizes 4/0 AWG, 500 kcmil, and 1000 kcmil aluminum 35kV cables. Reference [4] discusses the application of power cables to WPP collection systems and lists commonly used cable sizes as 1/0 and 4/0 AWG, and 500 and 1000 kcmil. Larger cable sizes such as 1250 and 1500 kcmil are also seeing more use. Factors to include in cable sizing include, among others, allowable ampacity, available short circuit current, and real power losses [4]. The 1/0 AWG cable must be used with care as, in the author's experience, the available fault current can exceed the capability of the cable and the cable has the highest resistance and therefore, also has the highest losses.

Table 5-1: 35kV cable data

Phase Conductor	4/0 AWG Al	500 kcmil Al	1000 kcmil Al	1000 kcmil Al with cross-bonded concentric conductors
Concentric Conductor	15-#12 AWG Cu	16-#12 AWG Cu	16-#12 AWG Cu	16-#12 AWG Cu
Positive Sequence Impedance (Ohms/1000 ft)	0.1034+j0.0520	0.0462+j0.0459	0.0252+j0.0422	0.0219+j0.0427
Shunt Admittance B/2, micro-Siemens/1000 ft	8.01	10.76	13.52	13.52
Assumed Ampacity (A)	250	390	510	540
Maximum number of 1.5 MW turbines at 0.90 PF	8	13	18	19

It is common to limit the number of cables in use to three or four. This eases the construction process and reduces the cable that must be stocked on an on-going basis for maintenance and repairs [4]. While not mentioned in [4], reducing the number of cable sizes used in the WPP also reduces the number of different cable accessories such as elbows and splice kits that must be stocked both during construction and for on-going maintenance. The data for the 35kV cable used in the test system is given in Table 5-1. Impedances for each branch in the system are provided in Appendix 1.

The impedances for the 35kV cable were calculated using the method outlined in [46] and physical data available from standard references. The cables in use on WPPs are typically equipped with both a conductor screen and an insulation screen. Because of this the shunt admittance was calculated using the formula provided for a tape-shielded cable on page 120 of [47] rather than the formula for a concentric neutral cable presented on page 118 of [47]. This is more consistent with the formulas provided in [48] (p. 6-6) and is consistent with standard practices at author's employer.

The ampacity values presented above are based on recent projects and are believed to be typical of projects in Iowa. Ampacity is determined largely by the thermal properties of the surrounding soil and the installation conditions and should be calculated specifically for each project [4]. Reference [13] limits the conductor temperature under normal operation to either 90 or 105 degrees C depending on the insulation design. It also notes that the materials used in the cable joints and terminations may not allow operation at 105 degrees C.

In overhead lines, wind blowing on the conductor provides cooling [49]. Underground cables do not benefit from this air movement and are instead surrounded by earth that acts as thermal insulation. Underground cables will virtually always have lower ampacities than overhead lines utilizing the same phase conductor [2].

Soil Thermal Resistivity

Soil thermal resistivity is discussed in [2], [4], and [50]. The soil thermal resistivity provides a measure of the thermal insulation provided by the soil [2]. While [2] and [4] do not directly state that high soil thermal resistivities result in reduced cable ampacities, comments related to improving thermal resistivity with special backfill materials in [2] and typical thermal resistivity values in [4] imply that higher values result in lower cable ampacities. This has been the author's experience.

The thermal resistivity value typically varies significantly based on the moisture content of the soil and the compaction level that is achieved after the cable has been installed.

High moisture content and low air content reduces the thermal resistivity [50]. Air content can be created by less-than-ideal compaction, which produces voids. These voids reduce the ability of the cable to dissipate heat and increase thermal resistivity. In the normal procedure, the soil resistivity is measured by obtaining several soil samples from the project site. A testing laboratory compacts these samples to the level that is expected to be achieved during construction and measures the thermal resistivity properties. The data from this the laboratory report are then used in the design studies [4].

References [4] and [50] note that cables carrying high currents have the tendency to dry the surrounding soil and as noted above, dry soils have higher thermal resistivity. This can result in a thermal runaway condition in which the heat from the cable dries out the surrounding earth, resulting in a higher conductor temperature that dries out the surrounding earth further [50].

The cable ampacity must be based on a stable operating point [50]. The method that appears to be advocated in [4] is to utilize a thermal resistivity value that assumes "dry-out conditions." Another method is described in [50]. In this method, the temperature at the junction between the cable and the earth (the "cable-earth interface") is restricted to a value that limits moisture migration. Reference [50] does not recommend the use of this method.

Grounding Concentric Conductors

Concentric neutral cables are used extensively in underground collection systems. These are single conductor cables constructed with strands of round wire wrapped concentrically around the insulation screen. This construction is typically referred to as jacketed concentric neutral cable and the round wire strands are called often called concentric neutrals [4]. Reference [4] notes that the term concentric "neutral" may not be correct in the WPP environment but rather argues that the term "shield wires" would be more accurate. (The WTG transformers are typically supplied with delta connected medium-voltage windings and grounded wye connected low-voltage windings [3], [7], though [3] notes that the grounded wye – grounded wye connection is also in use.) These will be referred to as "concentric conductors" for the remainder of this section.

Both the National Electrical Code [51] and the National Electrical Safety Code [52] require that the concentric conductors be grounded. The problem of grounding the shields in single conductor cables has been covered in several references including [4], [48] (pp. 6-22–24), [53], and [54]. Of these, [54] is the most complete and forms the basis of the remainder of this section except for references to WPP applications, which are based on [4] and the author's experience.

There are three common solutions to the problem of grounding of concentric conductors. The first and most common is "multi-point" grounding. In the multi-point grounding method, the concentric conductors are bonded to ground at both ends. This method creates circulating currents in the concentric conductors that increase losses and reduce the ampacity [54]. These losses can be reduced by using tight cable spacing like the "trefoil configuration." In this arrangement, the cables are placed in a tight, triangular bundle [4]. In the author's experience, a tight trefoil arrangement can be difficult to achieve compared to the "random lay," "flat," or "stacked" arrangements and reference [4] notes that random lay is the easiest arrangement to achieve. An alternative method of reducing the circulating currents is to reduce the concentric conductor conductivity (see formulas in Table 6-3 on page 6-23 of [48] or Table 1 in [53]). With the exception of circuits where the concentric conductors have been cross-bonded (see discussion below), the cables ampacities and impedances utilized in the test system model assume that the concentric conductors are multi-grounded in a triangular arrangement with some spacing between adjacent cables. The inclusion of some space between the conductors was intended to account for imperfect installation.

Using single-point grounding can eliminate circulating currents. In this method, the concentric conductors are only grounded at one end. This will result in a standing voltage at the ungrounded end of the cable that must be kept to acceptable levels. Additionally, these standing voltages create safety concerns that the design must address. The standing voltages can be reduced by limiting the cable length [54]. None of the cable segments in the test system model utilize this grounding method.

A commonly used method that significantly reduces circulating currents and allows for long cable runs is generally referred to as "cross-bonding." In this method, the cable section is divided into three equal segments. At the border between segments, the cable is broken and the concentric neutral strands are transposed or "cross-bonded." While this would in theory eliminate currents circulating in the concentric strands completely, in practical applications it does not eliminate them unless the cable is laid in a trefoil configuration, or an evenly spaced arrangement with the phase conductors transposed at the junctions as well. If this is not done, cross bonding produces a reduction in circulating currents rather than eliminating them. This method is particularly well suited to long cable segments. A major disadvantage to this method is that splices at the junctions between segments must not create a conductive shield path across the splice body [54]. Thus, the splice kits utilized for cross-bonded circuits will necessarily be different from the other splices in the WPP. As noted in Figure 5-1, several important cable segments in the test system utilize cross-bonded concentric conductors.

Substation Transformer Data

This example assumes that a single substation transformer will be used. This is one of the common arrangements discussed in [9]. The substation transformer used in the test system is a 100/133/167 MVA ONAN/ONAF/ONAF unit with an impedance of 0.25+j9.1%. The MVA rating was chosen based on maximum WTG production of 166.7 MVA (100-1.5 MW WTGs operating at 0.90 pf). The impedance is based on data from a similar size unit applied on a recent project. It is assumed that the transformer will not be equipped with a load tap changer. WPP transformers are not typically purchased with load tap changers due to higher initial and ongoing maintenance costs [9]. Reference [9] recommends avoiding them if possible. Transformers of this type are commonly equipped with no-load tap changers [9]. Load flow studies show that the optimal transformer no-load tap changer would be set at the 1.025 pu tap (meaning that the high-voltage winding is 141.5kV instead of 138kV). Use of an off-nominal tap is intended to offset a portion of the voltage rise through the transformer at high-load levels and avoids high collector system voltages at high generation levels.

The application of substation transformers in WPPs is discussed in [6] and [9]. In determining the optimal number of substation transformers, there are several factors to consider. The first group of factors is the practical. Of this group, the first is the size of the WPP. When currents at the substation bus exceed 3000A, suitable switches and bus tubing become expensive. Larger WPPs occupy larger geographic areas and these plants necessarily have longer collection circuits. This additional length may produce excessive voltage rise, necessitating the construction of a second substation to reduce the circuit length. Transporting large transformers in rural areas can also be difficult [9].

As noted in [4], short circuit currents are one factor in the design of the cable system. The short circuit capability of the cables is discussed in [48], [55] (cited in [48]), and [56]. Additionally, [10] specifies a maximum fault duty for 600A elbows of 25,000A if the fault is cleared in 10 cycles. Fault current magnitudes can be a problem on large WPP systems with only one substation transformer. While it may be possible to limit short circuit currents by utilizing reactors or higher than normal transformer impedances, installing two smaller substation transformers is one way of reducing fault current magnitudes, provided that they are not operated in parallel [9].

References [6] and [9] also discuss the issues surrounding the use of multiple substation transformers to increase “availability.” In a typical utility system, “reliability” (few service interruptions) is the primary goal, and tends to result in high levels of redundancy [6]. In WPPs, reliability is not as important as “availability” (delivery of available energy). The installation of a second substation transformer—even if it does not increase total transformation capacity—may result in increased availability as wind plants operate at less than 100% capacity a great deal of the time. This is especially true if the owner is willing to operate the transformer in excess of 100% of rated capacity. There are several factors to consider when making an economic justification to purchase multiple transformers. These include likelihood of a failure, time required for repair or replacement of a failed unit, impact on losses (two smaller transformers generally have higher losses than one larger transformer with the same total capacity), the installed cost of the transformers, and any ongoing costs such as taxes. This may, however, result in increased energy production when one of the transformers is out of service for maintenance or repairs if means to tie the medium voltage buses together are provided [9].

Transmission Line

Depending on the layout of the WPP and the location of the point of interconnect, the interconnect substation may be located at the WPP or at a separate location with a transmission line connecting the WPP substation and the interconnect switchyard [2]. The test system does not include a transmission line. It is assumed that the collection substation is located directly adjacent to point of interconnect. The point of interconnect is the substation 138kV bus.

Reactive Power Resources

A discussion of WPP reactive power compensation is provided in Chapter 4. The WTG reactive power capability is described in other portions of this chapter. A discussion of the other reactive power resources included in the test system model is included in Chapter 6.

Concerns in the determination of what reactive power resources are required include the power factor range that the WPP is required to provide, voltage(s) at which the power factor range must be provided, and whether or not smooth control of voltage or power factor is required. Power flow studies are typically used to study the proposed reactive power compensation systems to verify that interconnection requirements are met [1].

Chapter 6 Case Study in WPP Reactive Power Compensation and Centralized Control Methodologies

Reference [1] alludes to the centralized control systems that are often installed with large scale WPPs. These control systems are discussed further in Chapter 4 and in [25]–[32] and [35]. The proposed centralized control system is described in detail in Chapter 4. It is assumed that this central control system will be installed in the WPP substation, monitor the voltage and complex power flow at the substation, and utilize a PID control loop to regulate bus voltage. It is assumed that the reactive power dispatch created by the centralized control will be communicated to the WTGs using the fiber-optic network that is typically constructed alongside the medium-voltage collection system.

This chapter presents a case study undertaken to estimate the potential energy savings caused by the use of the centralized control system described in Chapter 4 if it were used to control the test system described in Chapter 5. The benchmark against which these results are compared is a control strategy that divides the reactive power equally amongst the WTGs.

Control System Strategies

The system losses were calculated with two different control strategies, which are described in the paragraphs that follow. In all cases, it is assumed that all WTGs will operate with the same real power injection. This assumption is made here for simplicity. Reference [30] states that a different wind speed prevails at each WTG and that the WTGs will all produce different amounts of real power.

Optimal Strategy

The first strategy, referred to as "optimal," assumes that the reactive power necessary to achieve the desired set point will be dispatched optimally amongst the turbines and substation resources by the centralized control system in order to minimize system losses while maintaining bus voltages within the limits described below. This is the controller described in Chapter 4.

Uniform Strategy

The second strategy, referred to as “uniform,” assumes that the central control system will divide the reactive power necessary to meet the set point evenly amongst the WTGs. This method has been utilized by author and author’s coworkers for design load flow studies performed for several WPPs. Given that it is assumed that all turbines will operate with the same real power injection, this assumption is consistent with the dispatch method described in [28]–[31].

A further simplifying assumption used for the uniform strategy is that the substation reactive power resources would only be used when the turbine capabilities were exhausted. The impact of this assumption is described in more detail below. The system limitations that this method was required to adhere to are not as extensive as the limitations placed on the “optimal” strategy and are discussed in more detail below. No data is available to compare this strategy with the commercially available WPP control systems such as the system described in [27].

Operating Conditions Studied

The reactive power that can be delivered to the transmission system is obviously limited by equipment capabilities. A key concern in selection of this equipment is that it must be capable of meeting the levels specified by the transmission provider [1]. Reference [1] discusses the requirements of FERC Order 661-A [23], which provides reactive power and low voltage ride through requirements in the portions of the United States outside of the ERCOT region. The reactive power requirements are discussed in more detail in Chapter 4.

The requirements investigated in this case study are described in more detail in the paragraphs that follow.

“Window” Requirement

The first operating condition, referred to as the “window,” only requires that the WPP operate with a power factor between 0.95 leading and 0.95 lagging, but does not specify that the WPP regulate to a power factor or voltage set point. This requirement is based on the assumption that the system impact study identifies a reliability need to constrain the amount of reactive power that the WPP is allowed to inject (or absorb) into the system, but does not identify a need for the WPP to provide voltage regulation. The issue of what requirements apply if no reliability need is identified is discussed in FERC Order 661-A [23]. Several respondents expressed concern regarding what requirements would apply if no reliability needs were identified. In issuing Order 661-A, FERC chose not to amend the final rule to address these concerns.

For simplicity it is assumed that the uniform reactive power dispatch will simply maintain a unity power factor at the point of interconnect. For the cases with optimal reactive power dispatch, the WPP is allowed to operate at any power factor between 0.95 leading and 0.95 lagging.

Requirements with Specific Set Points

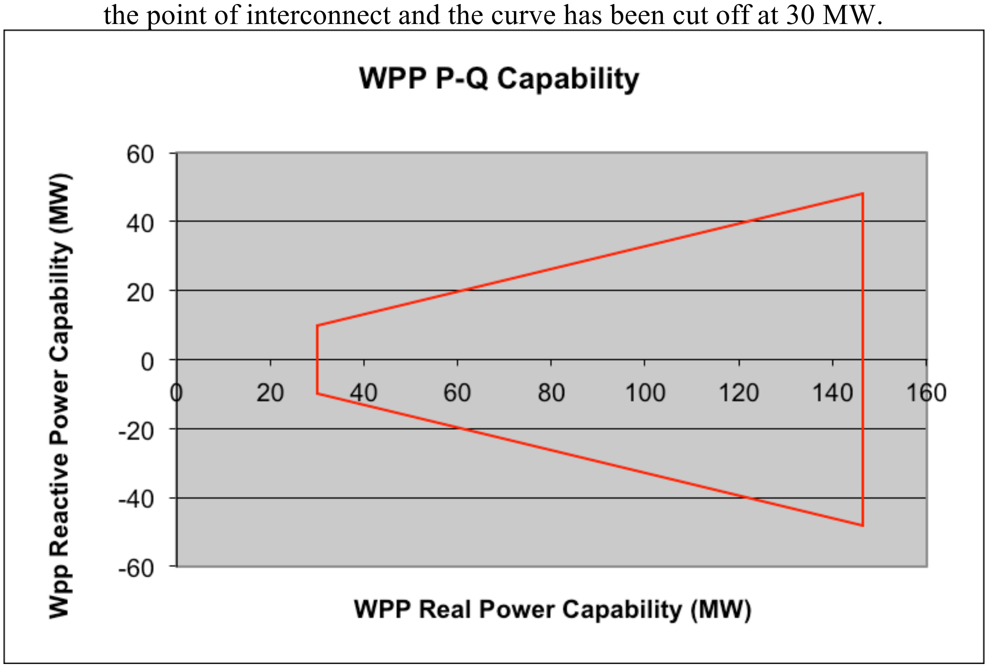
Reference [1] notes that the WPP may be required to regulate voltage or power factor to a specific set point. This case study assumes that the WPP will typically control voltage at the point of interconnect to a value specified by the transmission provider. Reference [1] also notes that the minimum reactive power requirements may take different forms. This paper has studied two specific requirements applied in two different ways for a total of four scenarios. These scenarios are discussed in more detail below.

For the purposes of this case study, it is assumed that the reactive power requirements would not apply when the WPP was operating at less than 20% generation. The UK Grid Code [57] requires that the WPP reactive power flow be less than 5% of WPP "rated MW output" when real power generation is less than 20% of the facilities capability. Similarly, ERCOT Nodal Protocols [24] only require that the reactive power capabilities be available when the WPP is at or above 10% of "nameplate capacity." These protocols also note that ERCOT may require that the WPP disconnect if it is operating at less than 10% generation and unable to support system voltage.

"Triangle" Requirement

The "triangle" requires that the wind plant meet any set point within a triangular shaped region between a power factor of 0.95 lead and 0.95 lagging. The magnitude of the reactive power that the wind plant must supply decreases with the real power generation. This requirement is shown in Figure 6-1. Note that because it is assumed that the requirement is relaxed at lower generation levels, the reactive power capability curve is actually shaped like a trapezoid. The language on FERC Order 661-A [23] is slightly different than the language in the ERCOT Nodal Protocols [24] and leads the author to interpret FERC Order 661-A [23] as requiring a capability curve similar to Figure 6-1 when necessary to maintain reliability. This matches the interpretations of FERC Order 661-A provided in [19].

Figure 6-1: "Triangular" reactive power capability.
The required reactive power capability decreases with real power generation. Note that maximum real power generation has been reduced from the total nameplate capacity of 150MW to account for real power losses between the WTG terminals and the point of interconnect and the curve has been cut off at 30 MW.

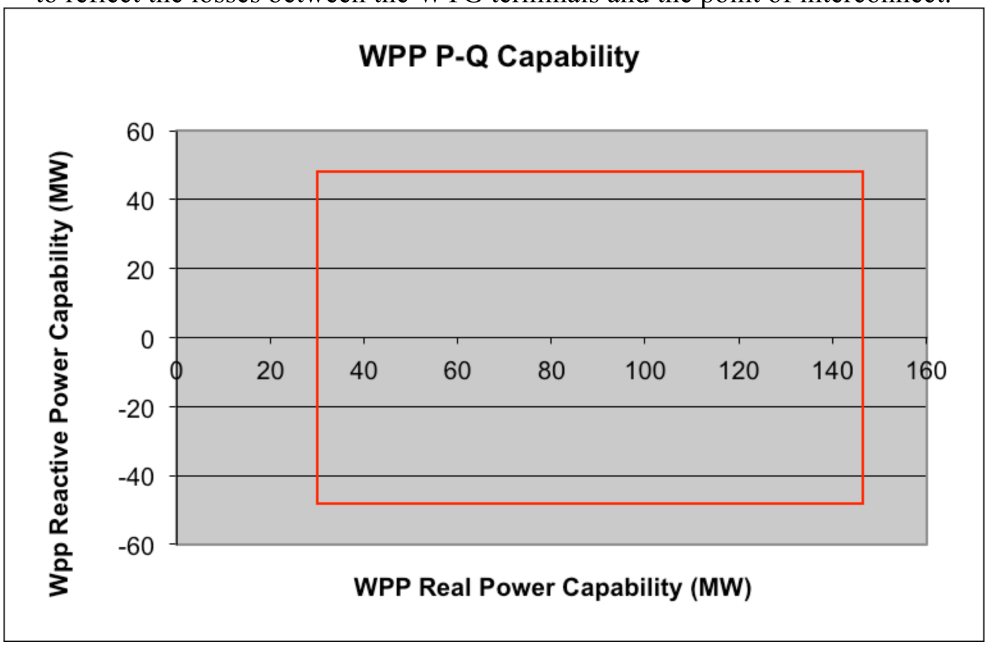


"Rectangle" Requirement

Reference [1] notes that the power factor range is not always constant over the range of real power generation. The "rectangle" condition requires that the WPP supply reactive power equivalent to 0.95 power factor leading or lagging at full generation over the entire range of real power generation. In this case, the quantity of reactive power that the WPP must be capable of supplying does not decrease with real power generation. This capability is shown in Figure 6-2. This is very similar to the requirements for new WPPs in the

ERCOT Nodal Protocols [24] and somewhat similar to the requirements of the UK Grid Code [57].

Figure 6-2: Rectangular reactive power capability requirement. Note that the required reactive power capability *does not* decrease with real power generation. As in Figure 6-1, the maximum real power generation has been reduced to reflect the losses between the WTG terminals and the point of interconnect.



Scenario Voltage Ranges

The reactive power capability of the wind plant varies with voltage. The reactive power supplied by shunt devices such as capacitors, reactors, and cable shunt admittance change with the square of voltage. Reactive losses in the cable system and transformers vary with the square of current [1] and current is obviously dependent on voltage. Additionally, the reactive power capability of certain WTGs is dependent on terminal voltage [5]. Reference [1] notes that the minimum reactive power requirements may need to be met at one point of interconnect voltage, or over a range of interconnect voltages. The implication of this is that the voltage(s) at which the WPP must be able to supply the required reactive power is an important factor in WPP design.

For the triangle and rectangle scenarios, this study investigates the difference in losses between the optimal and uniform dispatch under two assumptions, both of which are consistent with discussion in [1]. The first is that the wind plant is only required to have sufficient reactive power resources available to meet the minimum reactive power flow requirements when the bus voltage at the point of interconnect is at 1.0 pu. The second is that the wind plant is required to have sufficient reactive power resources available to meet the minimum reactive power flow at the point of interconnect when the voltage at the point of interconnect is between 0.95 and 1.05 pu. As discussed above, it was assumed that the reactive power flow requirements would not apply when the WPP was operating at less than 20% generation.

Substation Resources Included in Model

Table 6-2: Summary of operation scenarios studied.
Note that the rectangular and triangular cases are included twice, once with the requirement that the reactive power capability be met over a range of voltages, and the other with the requirement that the reactive power capability be met at one specific voltage.

Reactive Power Requirement	Must Specific Set Point Be Met?	Voltage Range Over Which +/-48.1 MVAR Requirement Must Be Met	Required Substation Reactive Power Equipment
Window	No	N/A	None
Rectangular	Yes	1.0 pu	1-6 MVAR, 35kV Capacitor
Rectangular	Yes	0.95–1.05 pu	2-14 MVAR, 138kV Capacitors 2-15 MVAR, 138kV Reactors
Triangular	Yes	1.0 pu	1-6 MVAR, 35kV Capacitor
Triangular	Yes	0.95–1.05 pu	2-14 MVAR, 138kV Capacitors

OPF solutions show that the maximum real power that can be delivered to the point of interconnect is 146.4 MW. Thus, the WPP must be capable of supplying or absorbing 48.1 MVAR in order to operate at 0.95 power factor at 100% generation. The substation reactive power resources required to meet the power factor requirements for each of the operation scenarios described above were determined by power flow and OPF analysis and are listed in Table 6-2.

As can be seen in Table 6-2, the quantity of substation reactive power resources can be heavily influenced by the voltage range over which the reactive power is expected to be delivered. For example, if the WPP is expected to provide significant quantities of reactive power with the point of interconnect bus voltage at high levels, it may not be possible to provide this reactive power from the WTGs as the voltage rise caused by reactive power flow in the WTG and substation transformers may be objectionable. If this is the case, it may be necessary to install substantial reactive power resources on the substation high voltage bus. Additionally, if the WPP is expected to absorb significant quantities of reactive power with the point of interconnect bus voltage at low levels, the voltage drop caused by reactive power flow in the WTG and substation transformers may be objectionable.

Cases Studied

Several cases were run for the scenarios listed above. These cases are intended to cover the full range of operation and are used to determine the difference in system losses between the two reactive power dispatch strategies. These include cases in which the voltage at the point of interconnect was at 0.95 pu, 0.975 pu, 1.0 pu, 1.025 pu, and 1.05 pu. Reference [58] specifies that the maximum voltage for a 138kV system is 145kV or 1.05 pu. This is used as the upper limit for the purposes of this case study. An arbitrary lower limit of 0.95 pu is used. While specific systems may occasionally operate outside of these limits, it is assumed that they would be of short duration and would not have a significant influence on the results though no data was available to confirm this.

For each of the four scenarios that required the WPP to meet a specific set point, cases were also run over a range of power factors. For the “triangle” reactive power requirement, cases were run at 0.95 and 0.975 power factor lag, 1.0 power factor, and 0.975 and 0.95 power factor lead. The choice of 0.95 power factor leading and lagging is based on [23] and. For the “rectangle” power factor requirement, cases were run with reactive power injections of +/-48.1 MVAR, +/- 33.4MVAR supply, and 0 MVAR. These are based on 0.95 and 0.975 power factor lag, 1.0 power factor, and 0.975 and 0.95 power factor lead at full generation and are similar to the windows set by [24].

For each of the four scenarios that required the WPP to meet a specific voltage set point, 260 cases were run. Of these, 130 cases each were run with the turbines dispatched optimally and another 130 cases each with the turbines dispatched uniformly. Of these 130 cases, 25 cases each were run with the WPP at 100%, 80%, 60%, 40%, and 20% generation. These 25 cases included five cases each with the 138kV bus at 0.95 pu, 0.975 pu, 1.0 pu, 1.025 pu, and 1.05 pu. These five cases covered operation of the WPP at unity power factor, two cases with the WPP operating with a leading power factor, and two cases with the WPP operating with a lagging power factor. The remaining five cases were run with the WPP operating 0% generation (no wind). These five cases covered operation with the 138kV bus at 0.95 pu, 0.975 pu, 1.0 pu, 1.025 pu, and 1.05 pu, and it was assumed that the WPP would operate to control the reactive power flow at the point of interconnect to 0 MVAR, though there is no specific basis for this assumption.

For the first "window" scenario, 30 cases each were run for the optimal and uniform dispatch. These covered operation at 100%, 80%, 60%, 40%, 20%, and 0% with the 138kV bus voltage operating at 0.95 pu, 0.975 pu, 1.0 pu, 1.025 pu, and 1.05 pu.

Uniform Dispatch System Limitations

The only limitations placed on the uniform dispatch solutions are caused by the capability of the WTGs. Figure 4-7 and Table 4-5 in [42] describe a portion of the dynamic model of one manufacturer's DFIG WTG. These imply that logic exists to prevent the terminal voltage at the WTG from straying above 1.10 pu or below 0.90 pu on a steady state basis though the model description does not confirm this. For the purposes of this study, it is assumed that the controls in the individual WTGs will have logic capable of overriding the reactive power request from the central control system if this request would cause the terminal voltage (690V bus) to fall outside of the range between 0.90 pu and 1.10 pu and reduce (or increase) the reactive power request to keep the WTG within its limits. It is also assumed that the centralized control system would not act to limit voltages on the 35kV collection system.

Optimal Dispatch System Limitations

One major advantage of using the OPF-based centralized control is the ability to prevent the system from operating in a fashion that would exceed predetermined limits. The limits placed on the OPF solution and the justifications for them are described in the following paragraphs.

Current Limitations

In the design of new large-scale WPPs, the maximum load is determined by the total maximum WTG generation capability. This is easy to calculate, and WPP collection systems are generally deliberately designed such that current limitations will not be exceeded.

Voltage Limitations

The discussion of voltage limitations provided in this section is based on analysis used by author and author's coworkers in the design of several medium voltage collection systems.

- Reference [10] specifies a maximum continuous operating voltage of 36.6kV or 1.061 pu on a 34.5kV base for cable elbows.
- Reference [11] specifies a maximum design voltage of 22kV for 35kV terminators. This is 1.10 pu on 34.5kV base
- Reference [12] does not specify a maximum continuous operating voltage for cable splices. For the purposes of this paper, it is assumed that the equipment ratings would not be more restrictive than ratings of the cable and elbows.
- Reference [13] specifies that the operating voltage for underground cable should not be higher than the rated voltage by more than 5% continuously and 10% for an emergency lasting not longer than 15 minutes. This implies that 35kV cable should not be operated continuously in excess of 36.75kV, or 1.065 pu on a 34.5kV base, and that the cable should not operate at a voltage higher than 1.116 on a 34.5kV base for longer than 15 minutes.

- Reference [45] limits the secondary voltage to 1.05 pu at full nameplate kVA rating and 0.80 power factor and 1.10 pu at no load. This implies that the primary winding voltage is allowed to be whatever is necessary to achieve a 1.05 pu secondary voltage. In the case of a WTG step up transformer, [59] defines the primary winding as the low voltage winding and the secondary winding as the medium-voltage winding provided that the transformer is suitable for step-up operation. The normal service conditions defined in [45] are for step down operation. If the 1750kVA transformer described in Chapter 5 is loaded to 1750kVA at 0.80 pf, the voltage rise through the transformer would result in a 690V winding voltage of approximately 1.09 pu. This calculation is shown in (6.1) below.

$$\left|1.05+\left(0.0074+j0.0574\right)\bullet\left(0.8-j0.6\right)\right|=1.091 \qquad (6.1)$$

The 690V winding voltage that would result from operating the WTG at full rated real and reactive power (1500kW and 726kVAR) is approximately 1.08pu. This calculation is shown in (6.2) below.

$$\left|1.05+\left(0.0074+j0.0574\right)\bullet\frac{1500-j726}{1750}\right|=1.081 \qquad (6.2)$$

- Surge arresters are commonly used in the medium-voltage collection system to protect the cable and transformers from voltage transients. Reference [60] recommends choosing surge arresters with 27kV duty cycle ratings for the substation transformer and 30kV duty cycle ratings elsewhere. These correspond to maximum continuous overvoltage ratings of 22kV and 24.4kV (line to ground), respectively [61]. This is 1.104 and 1.225 pu on a 19.92kV base. Reference [61] recommends utilizing an arrester with an MCOV rating that is higher than the maximum expected phase-ground voltage.

The voltage limitations on the 34.5kV buses were set at 0.88 and 1.075 pu. The upper limit is somewhat above the voltage levels described in the standards referenced above which would imply a limit of 1.05 or 1.061 pu but allows for the WTG to operate closer to full reactive capability. This is consistent with the limits operating voltage limits typically utilized by author and author's coworkers.

The minimum and maximum WTG terminal (690V) buses were set at 0.90 and 1.10 pu as discussed above.

MATPOWER Model

A model was built in the MATPOWER software package [41]. All branches (transformers and cable segments) and WTGs were modeled explicitly. The substation 138kV bus was treated as the slack bus. A load equal to the total WTG production as measured at the WTG terminals (i.e., 150MW for the 100% generation cases; 120 MW the 80% generation cases) was placed at the substation 138kV bus so that the slack generator would only supply system losses.

The MATPOWER software package does not have the capability to minimize system losses, but does provide an AC OPF algorithm that can minimize generation cost [41]. For the optimal model, both the upper and lower voltage limits on the substation 138kV bus were placed at the value desired for that particular case. The reactive load on the substation 138kV bus was set at the level that was required to be delivered to the bulk transmission system for that particular case. The incremental cost for the WTGs was set at $0/MWHr. The slack bus generator was set at $80/MWHr to force the slack generator to generate as little real power as possible. These values were arbitrarily chosen, any values would suffice as long as the incremental costs for the WTGs were lower than the slack bus generator. For the slack bus generator, the maximum and minimum reactive power generation were set to zero to force all reactive power to be generated by the WPP. The maximum power limit for each WTG was set at the desired value for that case (i.e., 1.5 MW for 100% generation, 1.2 MW for 80% generation, etc).

MATPOWER also possesses a standard AC power flow algorithm that was used for the uniform cases. For these cases, the WTG real power generation was set at the required level. The slack bus voltage was set at the value desired for that case. The slack bus load was set with zero reactive power demand. Each WTG was treated as a P-Q bus with the real power injection set to the desired value for that case (i.e., 1.5 MW for 100% generation, 1.2 MW for

80% generation, etc). The reactive power injection for each WTG was changed until the reactive power injection by the slack bus generator reached the desired value. If a particular WTG 690V bus voltage reached dropped below 0.90 pu or exceeded 1.10 pu, that unit was changed to a P-V bus and the other WTG reactive power injections were adjusted accordingly.

Results

In total, 1100 cases were run. The differences in losses between the optimal and uniform dispatch were then compared for each case. A summary of the potential energy savings at 100% generation created by optimally dispatching reactive power resources is provided in Table 6-3.

Table 6-3: Summary of potential real power savings at 100% generation. Note that in certain cases, the optimal reactive power dispatch actually produces higher losses than the uniform dispatch case due to the additional voltage constraints imposed on the solution.

Reactive Power Requirement	Voltage Range Over Which +/-48.1 MVAR Requirement Must Be Met	Range of Potential Power Savings Due to Optimal Dispatch of Reactive Power (kW)
Window	N/A	6.8–11.3
Rectangular	1.0 pu	-304.6–127.0
Rectangular	0.95–1.05 pu	-230.0–354.0
Triangular	1.0 pu	-304.2–127.0
Triangular	0.95–1.05 pu	-230.3–197.2

The cases in which the optimal solution actually produced higher losses are caused by the voltage constraints that are placed on the optimal reactive power strategy but not on the uniform strategy. These cases are expected to occur infrequently as they are caused by cases where the transmission system voltage is low and the WPP is absorbing large quantities of reactive power or the transmission system voltage is high and the WPP is generation large quantities of reactive power.

The difference in losses was then multiplied by the hours per year that the WPP would be expected to operate at that particular level. From this information, the total difference in losses between the various scenarios can be calculated. Unfortunately, data showing how many years a typical WPP operates at a given level were not available and were estimated. In estimating the number of hours per year that the WPP would operate at a particular level, the assumptions listed below were made.

- When a specific set point is required to be met, the WPP will control voltage at the point of interconnect to a value that varies based on system conditions but will be between 1.0 pu and 1.05 pu.
- The WPP will be connected to a system that is neither strong nor weak, implying that the WPP will have a significant impact on system voltage levels, but will not always be capable of supplying (or absorbing) sufficient reactive power to regulate the bus voltage to the desired set-point. This implies that the bus voltage will stray from the set point during normal operation, but should remain close.
- The WPP will spend the hours listed in Table 6-4 per year at each respective generation level, regardless of the case. This data was taken from the average of several recent WPP projects.

Table 6-4: Hours spent per year at each generation level.
Note that this produces a yearly capacity factor of approximately 46%.

Generation Level	Hours/Year
100%	1100
80%	1300
60%	1400
40%	1600
20%	2000
0%	1360

With the assumptions described above, the hours that WPP operations would approximate each case was estimated, and the total difference in losses between the uniform and optimal dispatch were calculated and appear in Table 6-5.

Table 6-5: Estimated annual energy savings.

Reactive Power Requirement	Voltage Range Over Which +/-48.1 MVAR Requirement Must Be Met	Estimated Annual Energy Savings (MWhr)
Window	N/A	18
Rectangular	1.0 pu	372
Rectangular	0.95–1.05 pu	1,358
Triangular	1.0 pu	140
Triangular	0.95–1.05 pu	339

Chapter 7 Discussion of Results

System Losses

The results show that the majority of the difference between the optimal and uniform dispatches comes from utilizing the substation reactive power resources more effectively. To demonstrate this, five cases were run using the "rectangular" case with the 0.95 –1.05 pu voltage requirement. The uniform reactive power dispatch strategy described in Chapter 6 was used except that the substation resources were utilized in the same manner as the results from the optimal dispatch strategy. The results of this are shown in Table 7-1.

Table 7-1: Comparison between substation resource dispatch strategies. "Uniform-Optimal" utilizes the original uniform dispatch strategy. "Uniform Alternate-Optimal" utilizes the alternate dispatch described above.

	Difference in Losses (kW)				
Reactive Power Flow at POI	48.1 MVAR Supply	33.4 MVAR Supply	0 MVAR	33.4 MVAR Absorb	48.1 MVAR Absorb
Uniform - Optimal	147.5	178.6	6.3	204.1	347.3
Uniform Alternate - Optimal	27.9	10.5	6.3	4.1	1.4

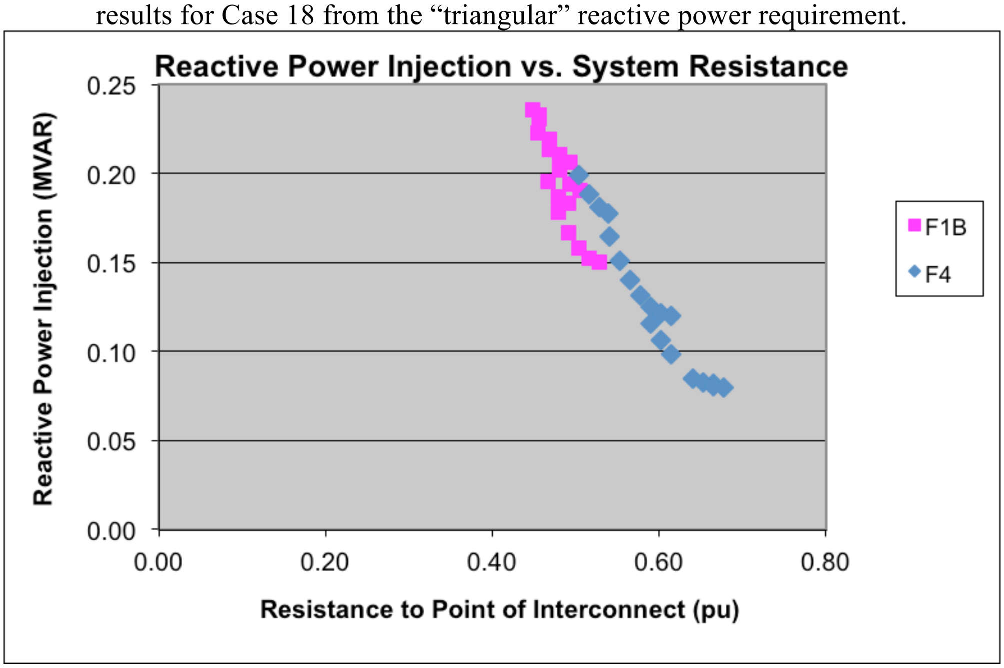
The OPF results for the "window" cases offer some insight as to the optimal operating point for the WPP. Surprisingly, the results show that it is most efficient for the wind farm to deliver between 1.4 and 4.1 MVAR to the point of interconnect depending on the voltage at the point of interconnect. It was anticipated that the optimal operating point would be to have the WPP absorb modest quantities of reactive power.

Reactive Power Injections

Normal Conditions

As expected, the results show an inverse relationship between the total resistance measured at the WTG terminals and the reactive power injection under normal operating conditions. Also as expected, the WTGs that are closest electrically to the point of interconnect inject the most reactive power while the WTGs that are furthest electrically inject the least. This relationship is illustrated in Figure 7-1, which shows a plot of the reactive power injected by the WTGs on two of the test system's six collection circuits versus total resistance between the WTG terminals and the point of interconnect. Circuit F1B is the collection circuit containing the WTG that is electrically closest to the point of interconnect. Circuit F4 contains the most electrically distant WTG. The case shown in Figure 7-1 was chosen because it was assumed that this would be the maximum generation case that occurs most frequently.

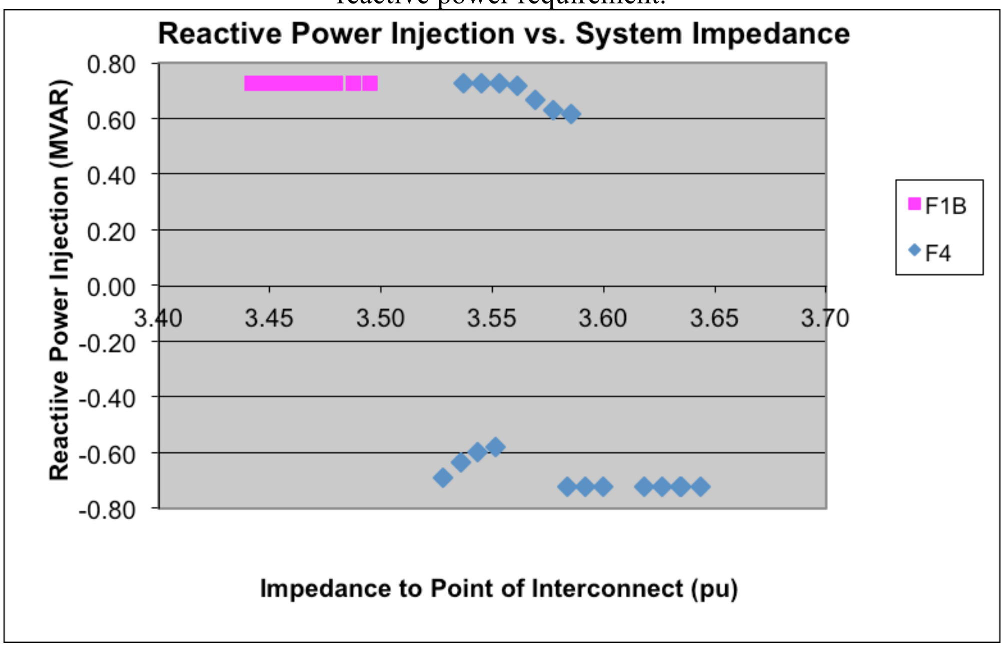
Figure 7-1: WTG reactive power injection versus system resistance under normal conditions utilizing the optimal reactive power dispatch strategy.
Note that only two collector circuits are shown for clarity. The figure shows the results for Case 18 from the "triangular" reactive power requirement.



As can be seen in Figure 7-1, the relationship between resistance to the point of interconnect and reactive power injection is not perfect. This is to be expected because losses in a given branch are proportional to resistance multiplied by the square of the current and the optimal reactive power injection is therefore dependent on the other WTGs. The case shown in Figure 7-1 is expected to be a fairly common occurrence. In this case, the WPP is operating at full capacity, is supplying 0 MVAR to the transmission system, and the point of interconnect is operating at 1.025 pu. In this case, the solution is not limited by any voltage constraints.

Extreme Conditions

Figure 7-2: WTG reactive power injection versus system impedance under extreme conditions utilizing the optimal dispatch strategy.
Note that the x-axis begins at 3.4 pu. Total system impedance is used in lieu of the system resistance that was used in Figure 6-1 as voltage rise is affected by total system impedance. This figure shows the results for Case 21 from the "triangular" reactive power requirement.



While the results show that the optimal reactive power controller will generally reduce system losses, under certain situations, the optimal solution will actually produce losses that exceed those produced by the uniform cases. This is due to more restrictive voltage constraints that are imposed on the optimal solution over the similar cases utilizing the uniform dispatch method. These situations arise in two fashions. The first is where the interconnect bus voltage is high and the WPP is expected to supply significant quantities of reactive power. In these cases, 34.5kV bus voltages restrain the OPF and some of the electrically more distant WTGs absorb reactive power to reduce the voltages on the more remote 34.5kV buses. The WTGs that are closer to the substation in turn generate additional reactive power to compensate. A similar situation occurs at low interconnect bus voltages (0.95 pu) when the WPP is being asked to absorb reactive power. The cases where this happens are expected to occur infrequently but are more extreme in cases where the WPP does not have significant substation reactive power resources.

Figure 7-3: WTG reactive power injection versus system impedance under extreme conditions utilizing the uniform dispatch strategy.
Note that only two collector circuits are shown for clarity and that the x-axis begins at 3.4 pu. This figure shows the results for Case 21 from the "triangular" reactive power requirement.

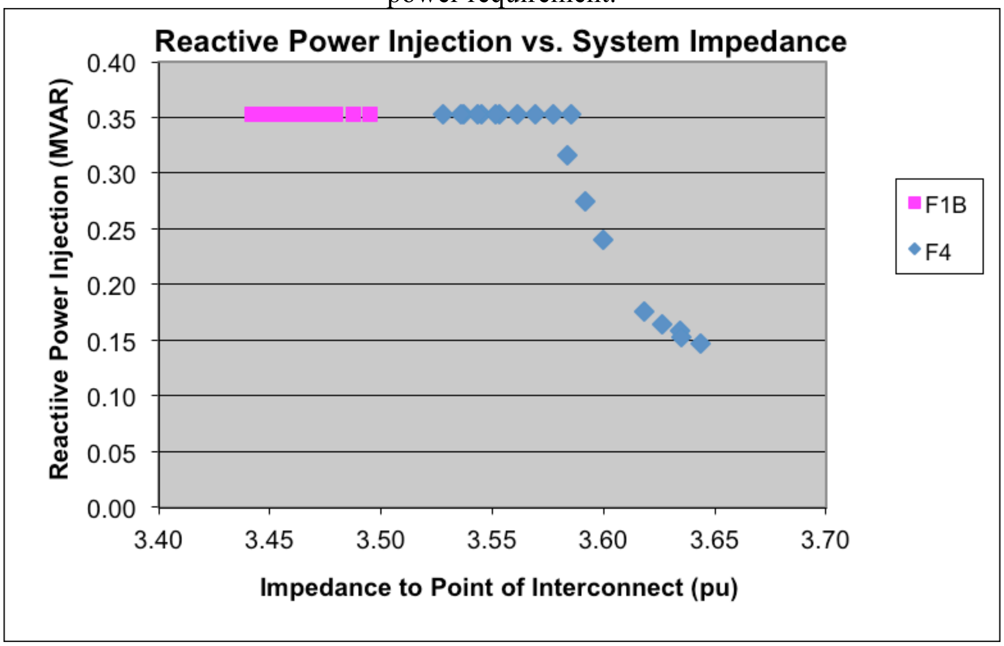


Figure 7-2 and Figure 7-3 are scatter plots of reactive power injections versus system impedances for Case 21 with the "triangular" reactive power requirement. In this case, the bus voltage at the point of interconnect is 1.05 pu and the WPP is asked to deliver maximum reactive power. Figure 7-2 shows a plot of the reactive power injected by the WTGs on two of the test system's six collection circuits versus total system impedance between the WTG terminals and the point of interconnect.

Figure 7-2 clearly shows that when utilizing the optimal dispatch algorithm, the WTGs can be divided into two groups. The first group is injecting close to maximum reactive power; the second, smaller, group is absorbing close to maximum reactive power to hold bus voltages on the medium-voltage collection system within limits. In this case, the correlation between reactive power injection and system impedance is significantly less than in the case depicted in Figure 7-1. However, the general trend is that the WTGs that are more distant electrically from the point of interconnect are more likely to be absorbing reactive power than the WTGs that are closer to the point of interconnect. There is a significant contrast between the reactive power injections shown in Figure 7-2 and the injections from the corresponding uniform dispatch case, which are shown in Figure 7-3.

As can be seen in Figure 7-3, the reactive power injections are uniform with the exception of some of the more distant WTGs, whose injections are reduced to prevent the WTG terminal voltage from exceeding 1.10 pu. Note that in the uniform dispatch case, all WTGs inject reactive power into the system and none absorbs reactive power. This is significantly different from the results obtained utilizing the optimal dispatch algorithm.

Voltage Profile

Normal Conditions

Also of interest are the differences between the voltage profiles created by the two reactive power dispatch methods. A plot of 34.5kV bus voltages versus system impedance created by the optimal dispatch method is shown in Figure 7-4. Note that these bus voltages are from the same case as the reactive power injections in Figure 7-1.

Figure 7-4: WTG 34.5kV bus voltage versus system impedance under normal conditions utilizing the optimal dispatch strategy.
This figure shows the results for the optimal strategy for Case 18 from the "triangular" reactive power requirement.

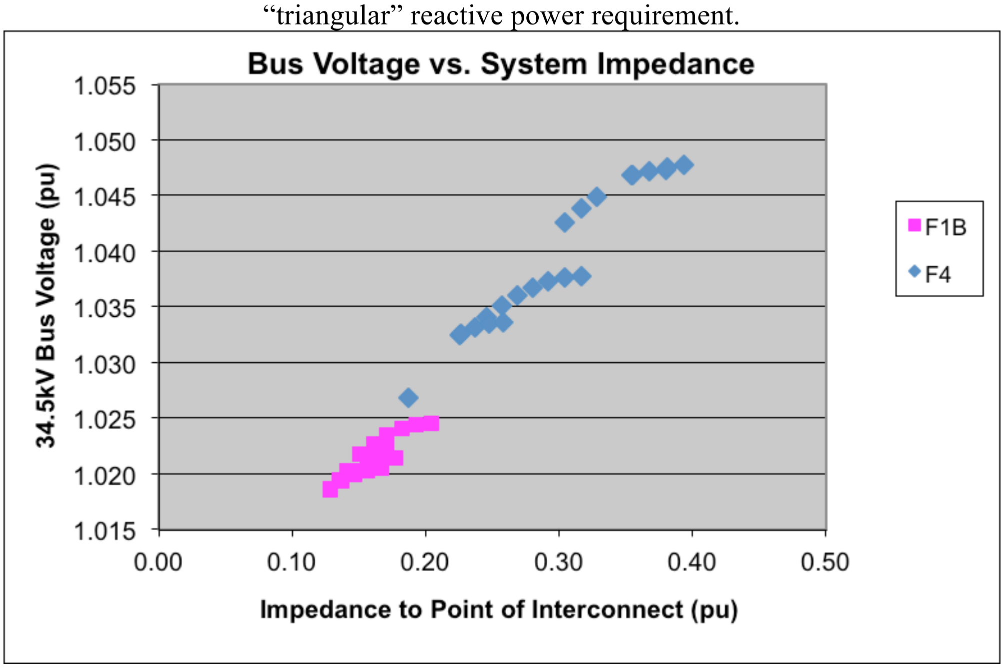


Figure 7-5 shows a plot of bus voltages versus system impedance for the same case as Figure 7-4 but with the results from the uniform dispatch method. As can be seen by comparing Figure 7-4 to Figure 7-5, the voltage profile created by the two dispatch strategies is similar under normal circumstances. Table 7-2 shows a summary of the 35kV bus voltage profiles resulting from Case 18 with the "triangular" reactive power requirement.

Figure 7-5: WTG 34.5kV bus voltage versus system impedance under normal conditions utilizing the uniform dispatch strategy.
This figure shows the results for the uniform strategy for Case 18 from the "triangular" reactive power requirement.

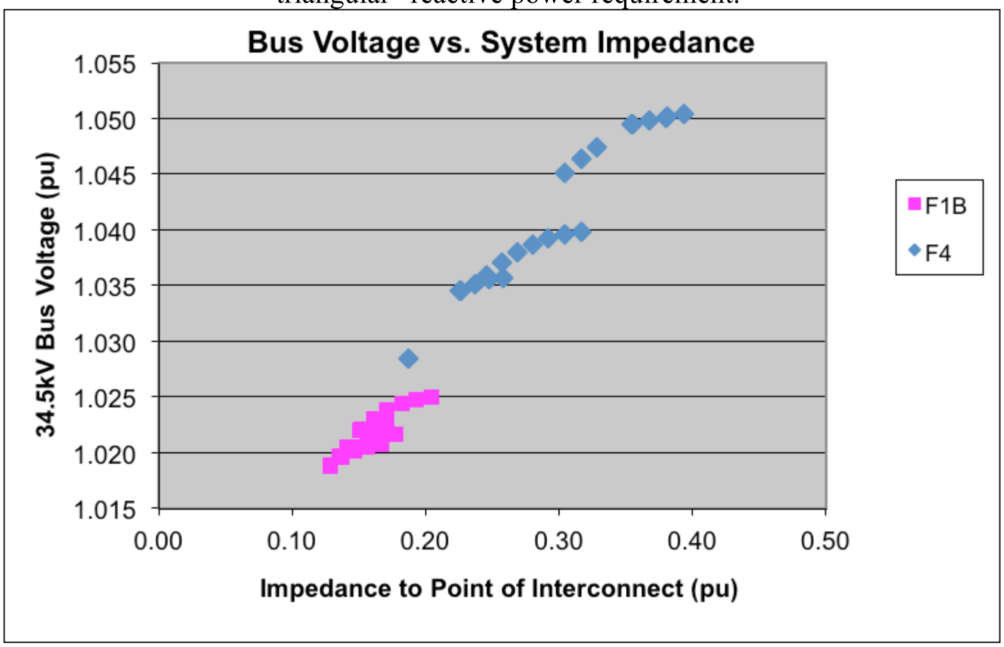


Table 7-2: Summary of voltage profiles created by two reactive power dispatch strategies under normal conditions.

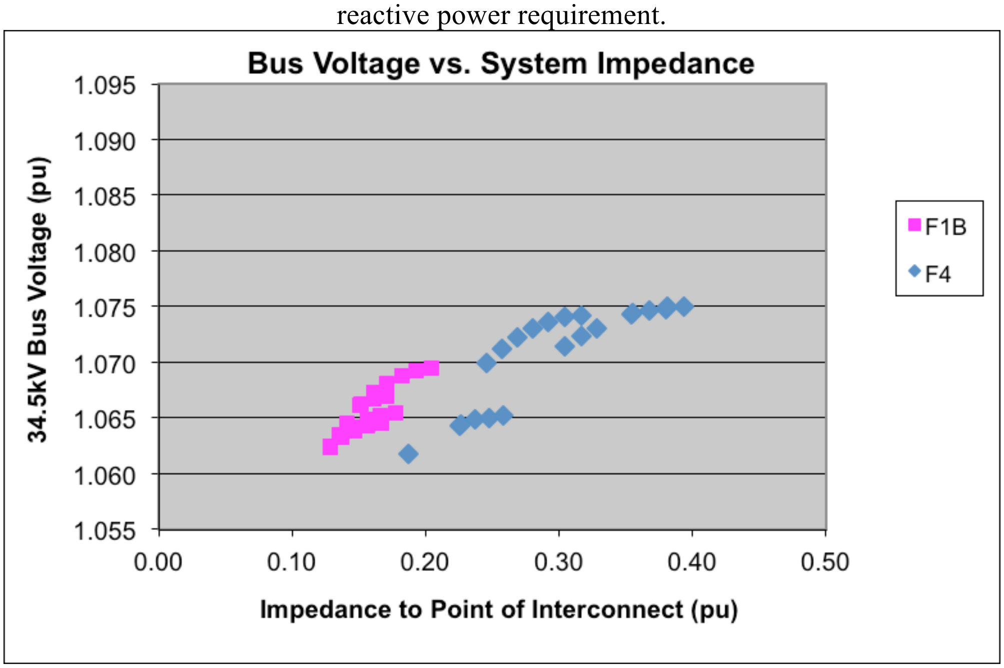
	Optimal Strategy	Uniform Strategy
Minimum 34.5kV Bus Voltage	1.0165 pu	1.0165 pu
Maximum 34.5kV Bus Voltage	1.0477 pu	1.0504 pu
Average 34.5kV Bus Voltage	1.0283 pu	1.0293 pu

Table 7-2 shows that under conditions where bus voltages are less than the constraints, the voltage profiles created by the two dispatch strategies are similar. The voltage profile for the optimal strategy is somewhat less than the uniform strategy; however, some of this is due to the fact that the optimal solution deployed one 6 MVAR substation capacitor whereas the uniform strategy deployed none.

Extreme Conditions

Under extreme conditions, the voltage profile created by the two strategies differs significantly. The optimal strategy is forced to constrain the 34.5kV bus voltages to 1.075pu, whereas the uniform strategy only restricts the 690V bus voltages to 1.10 pu or less. Figure 7-6 and Figure 7-7 show the voltage profile on the 34.5kV system under the same conditions as the scatter plots in Figure 7-2 and Figure 7-3. The voltage profile created by the optimal strategy under these conditions is shown in Figure 7-6.

Figure 7-6: WTG 34.5kV bus voltage versus system impedance under extreme conditions utilizing the optimal dispatch strategy.
This figure shows the results for the optimal solution to Case 21 with the "triangular" reactive power requirement.



The voltage profile created by the uniform dispatch strategy under the same conditons as the results shown in Figure 7-6 is shown in Figure 7-7. These figures clearly show that there is a siginificant difference between the voltage profiles created using the optimal and uniform strategies under more extreme conditions. As can be seen in Figure 7-6, the requirement to maintain the 34.5kV bus voltages at or below 1.075 is a much more severe requirement than the requirement to maintain the 690V bus voltages at no more than 1.10 pu. Table 7-3 shows a summary of the collection system 34.5kV bus voltages under the more extreme conditions. Note that the bus voltages created by the uniform strategy are significantly higher than the voltages created by the optimal strategy.

Figure 7-7: WTG 34.5kV bus voltage versus system impedance under extreme conditions utilizing the uniform dispatch strategy.
This figure shows the results or the uniform solution to Case 21 with the "triangular" reactive power requirement.

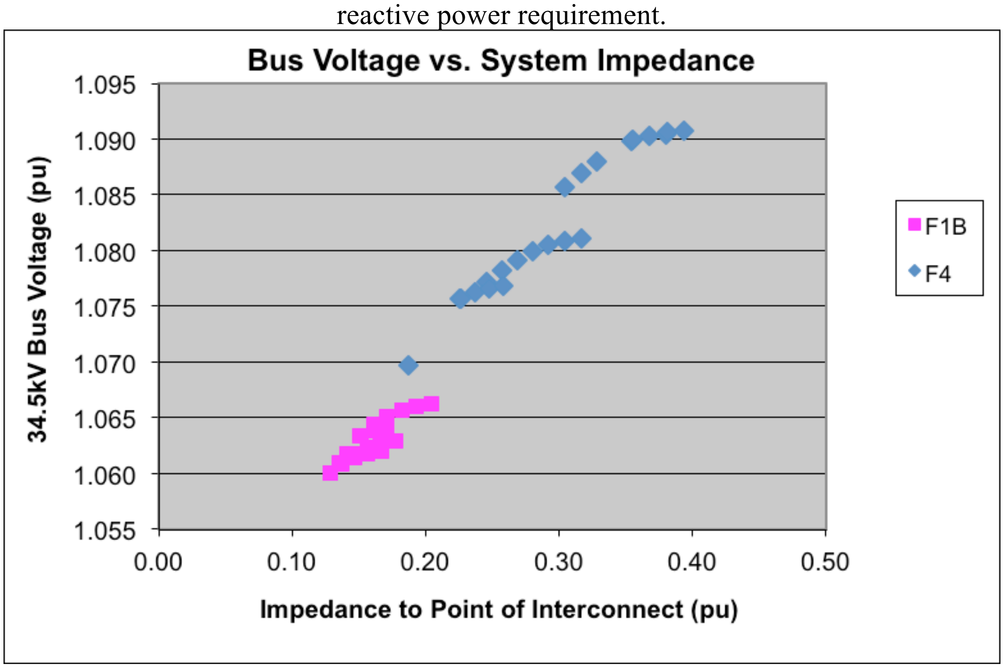


Table 7-3: Summary of bus voltage profiles created by two reactive power strategies under extreme conditions.

	Optimal Strategy	Uniform Strategy
Minimum 34.5kV Bus Voltage	1.0576 pu	1.0571 pu
Maximum 34.5kV Bus Voltage	1.0750 pu	1.0908 pu
Average 34.5kV Bus Voltage	1.0679 pu	1.0706 pu

Cost Effectiveness

The net present value method of making project investment decisions is described in [62]. In order to determine the present value of the losses that are avoided by using the proposed control strategy over the “uniform” strategy, it is first necessary to determine the present value of the avoided losses and the present value of incremental expenditures necessary to purchase and install the OPF based control system. The net present value is then the money remaining after the present value of the incremental cost of the improvements is subtracted from the present value of the avoided losses.

Present Value of Avoided Losses

The present value of the avoided losses is obviously dependent on the cost of the energy produced by the WPP. Lawrence Berkeley National Laboratory has compiled market data on WPPs and the power purchase agreements (PPA) through which the energy is typically sold. A summary of this research is provided in [63]. The typical WPP built in 2009 averaged 91 MW, was owned by an independent power producer, and the energy was sold through a long term PPA. For projects constructed in 2009, the average sale price of wind energy sold under a power purchase agreement was \$61/MWhr [63]. According to Figure 20 in [63], PPA prices for projects completed in 2009 ranged from \$40/MWhr to \$85/MWhr. These prices do not include the renewable energy production tax credit (PTC) [63]. Discussion in [64]–[66] provides an outline of a PPA that was proposed in proceedings before the Iowa Utilities Board. In this case, an independent power producer offered to sell energy from two WPPs for a period of 25 years at a cost of \$54.06/MWhr with a yearly cost increase of 2% [64], [65].

The PTC is available for the first 10 years after commercial operation commences and is adjusted for inflation [67], [68]. In tax year 2010, the value of this tax credit was \$0.022/kWhr or \$22/MWhr [68], [69].

Discussion in [66] quotes testimony from the independent power producer where they stated that they generally do not proceed with a project unless the return on equity is in “the teens or the twenties” (quoted on p. 80) whereas the regulated utility was requesting a return on equity of 12.2% to build its own WPPs [66].

Reference [70] provides formulas for calculating the present value of a series of cash flows. The formula for calculating the present value of a geometrically increasing series is provided in Equation (4.26) in [70] (p. 147). This is repeated in (7.1) below.

$$P = A_1 \frac{1-(1+g)^N (1+i)^{-N}}{i-g} \quad if\ i \neq g$$

$$or$$

$$P = \frac{N \cdot A_1}{1+i} \quad if\ i = g \tag{7.1}$$

Where:

- P is the present value of the series of cash flows
- A_1 is the cash flow at the end of the first period
- g is the change, in percent, of the cash flow between consecutive periods
- i is the interest rate
- N is the number of periods

Table 7-4: Summary of loss value scenarios.

	High Energy Value	Middle Energy Value	Low Energy Value
Initial PPA Energy Price ($/MWhr)	$80	$60	$40
Minimally Attractive Rate of Return (%)	10%	15%	20%
PPA Escalation (%/year)	2%	2%	2%
PPA Duration (years)	25	25	25
Initial PTC Value ($/MWhr)	$22	$22	$22
PTC Inflation Adjustment (%/year)	3.2%	3.2%	3.2%
PTC Duration (Years)	10	10	10
Calculated Present Value of Avoided Losses ($/MWhr)	$1000	$560	$320

It is possible to calculate a range of possible values for a MWhr of loss that is avoided each year. Because of the substantial variation in values provided in the information above, three scenarios were calculated using (7.1) and are shown in Table 7-4. The assumed inflation rate is based on information presented in [71] which implies an annual inflation rate of 3.2% in the 30 years between 1981 and 2010.

Present Value of Costs of the Proposed Control System

It is difficult to forecast the costs of the proposed control system and the Author is not aware of any published data that would serve as a useful reference. As mentioned in Chapter 4, much of the hardware necessary to implement the control system is already present at most WPPs. The development costs for the control software would be spread across several WPPs; however, there would be costs associated with setting up and tuning the algorithm for each individual WPP. Estimated incremental costs associated with the installation and maintenance of the proposed system were calculated using (7.1) and are given in Table 7-5.

Table 7-5: Assumed incremental costs of proposed control system.

	High Energy Value	Middle Energy Value	Low Energy Value
Upfront Set-Up Costs	$100 000	$100 000	$100 000
Average Yearly Maintenance Costs ($/Year)	$10 000	$10 000	$10 000
Minimally Attractive Rate of Return (%)	10%	15%	20%
Inflation Rate (%/year)	3.2%	3.2%	3.2%
Site Life (years)	25	25	25
Calculated Present Value of System Costs	$220 000	$180 000	$160 000

The estimates presented in Table 7-5 are not based on any published data but rather on the assumption that the proposed system is an incremental improvement over the centralized control systems that are already installed at a large number of WPPs.

Net Present Value of Proposed Control System

Using the values presented in Table 6-5, Table 7-4, and Table 7-5, it is possible to calculate the net present value of the proposed control system. The estimated net present value of the control system proposed in Chapter 4 is shown in Table 7-6. As expected, the cost effectiveness depends heavily on the amount of reactive power that the WPP is expected to provide to the transmission system and the value of the energy. Using the assumptions described above, the proposed control system can be justified on the basis of cost savings in 7 of the 15 cases that were analyzed.

Table 7-6: Estimated net present value of proposed control system.

Reactive Power Requirement	Voltage Range Over Which +/- 48.1 MVAR Requirement Must Be Met	Estimated Annual Energy Savings (MWhr)	High Value Energy	Middle Value Energy	Low Value Energy
Window	N/A	18	($202 000)	($169 920)	($154 240)
Rectangular	1.0 pu	372	$152 000	$28 320	($40 960)
Rectangular	0.95–1.05 pu	1,358	$1 138 000	$580 480	$274 560
Triangular	1.0 pu	140	($80 000)	($101 600)	($115 200)
Triangular	0.95–1.05 pu	339	$119 000	$9 840	($51 520)

Significant Assumptions

Several significant assumptions that were made and conjecture on their potential impact on the study results are given below.

- While there has been some discussion of centralized control systems in the literature, a discussion of which is provided in Chapter 4, the strategies used by commercial centralized control systems is unknown. The author has utilized the uniform dispatch method described here for recent studies; however, it should not be considered an accurate representation of a commercially available system.
- As discussed above, a significant portion of the difference between the optimal and uniform dispatch methodologies comes from the assumption that the uniform dispatch will utilize the substation resources last, whereas the optimal dispatch tends to use

them first. If it were assumed that the uniform dispatch utilized the substation reactive power resources first, the difference between the two methods would be less.

- Data showing the hours that the WPP would spend at each generation level were taken from the average of several sites and are believed to be typical.
- Data showing the variation of the interconnect bus voltage and reactive power injections over time were not available and would likely vary considerably from location to location. This means that the hours spent operating at each case were not available, and assumptions were made to create this data.
- This study assumes that the WTGs will all operate at the highest real power injection allowed by the prevailing winds at all times. For simplicity, it was assumed that all WTGs would operate at an equal generation level. Under normal operations, the wind speed may be different across the wind plant. This may cause individual WTGs to produce different levels of real power at the same time [30].
- No data was available to provide an accurate cost estimate of the incremental costs of the proposed control system. Data used to determine cost effectiveness is estimated.

Conclusion

Using the data presented here, it appears that while a centralized control system that integrates an OPF algorithm will reduce system losses, the reduction in losses is smaller than the author had anticipated. An important advantage of this control system is the ability to force the reactive power dispatch to respect voltage constraints.

It appears that an economic justification for utilizing the proposed OPF based centralized control system may exist at WPPs with higher energy values. The author feels that the control system would be most useful in very large WPPs with long collection circuits. In these WPPS, the long collection circuits cause increased losses and voltage regulation problems and a control system that accounts for the system impedance between the WTG terminals and the point of interconnect would provide the most benefits in such a system.

Oportunities for Further Work

Opportunities for further advancement of the control system are provided in Chapter 4. The analysis of cost effectiveness could be refined in several ways. Most of these revolve around clarifying the significant assumptions listed above. The estimate of the incremental loss savings could be improved by using real WPP systems with historical data showing the number of hours that the wind plant operates at various combinations of interconnect bus voltage and real and reactive power injections. Additionally, the estimate of incremental loss savings could be improved by comparing the proposed control system to a commercial control system. The economic analysis could be improved by using economic data from actual projects and by developing a detailed estimate of the incremental cost to install the proposed OPF based centralized control system.

This thesis has presented detailed steady-state studies. Another possibility for further study is detailed time-domain studies to show the dynamic performance of the control system to changing system conditions.

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Appendix 1 Test System Medium Voltage Cable Impedances

Table A1-1: 35kV cable impedances used in test system.

From Bus Name	To Bus Name	Length (ft)	Cable Type	R1 (Ohms)	X1 (Ohms)	B1 (Micro Siemens)	R1 (pu)	X1 (pu)	B1 (pu)
Sub	T1	5000	Al-4/0 AWG	0.5170	0.2600	80.1100	0.0434	0.0218	0.000954
T1	T2	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T2	T3	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T3	T4	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T4	T5	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T5	T6	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
Sub	JB11	10000	Al-1000 kcmil XB	0.2190	0.4270	270.4600	0.0184	0.0359	0.003219
JB11	T7	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T7	T8	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T8	T9	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T9	T10	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T10	T11	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB11	JB12	100	Al-1000 kcmil	0.0025	0.0042	2.7046	0.0002	0.0004	0.000032
JB12	T12	1400	Al-500 kcmil	0.0647	0.0643	30.1224	0.0054	0.0054	0.000359
T12	T13	1400	Al-500 kcmil	0.0647	0.0643	30.1224	0.0054	0.0054	0.000359
T13	T14	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T14	JB13	100	Al-4/0 AWG	0.0103	0.0052	1.6022	0.0009	0.0004	0.000019
JB13	T15	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T15	T16	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB13	T17	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T17	T18	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T18	T19	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T19	T20	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T20	T21	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB12	T22	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T22	T23	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T23	T24	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T24	T25	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
Sub	JB21	10000	Al-1000 kcmil	0.2520	0.4220	270.4600	0.0212	0.0355	0.003219
JB21	T26	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T26	T27	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T27	T28	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T28	T29	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T29	T30	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB21	T31	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T31	T32	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T32	T33	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T33	T34	5000	Al-4/0 AWG	0.5170	0.2600	80.1100	0.0434	0.0218	0.000954
T34	T35	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T35	T36	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267

Table A1-1: 35kV cable impedances used in test system (continued).

From Bus Name	To Bus Name	Length (ft)	Cable Type	R1 (Ohms)	X1 (Ohms)	B1 (Micro Siemens)	R1 (pu)	X1 (pu)	B1 (pu)
T36	T37	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T37	T38	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB21	T39	6100	Al-4/0 AWG	0.6307	0.3172	97.7342	0.0530	0.0266	0.001163
T39	T40	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T40	T41	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T41	T42	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T42	T43	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
Sub	JB31	15000	Al-1000 kcmil XB	0.3285	0.6405	405.6900	0.0276	0.0538	0.004829
JB31	T44	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T44	T45	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T45	T46	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T46	T47	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T47	T48	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T48	T49	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB31	T50	8000	Al-500 kcmil	0.3696	0.3672	172.1280	0.0311	0.0309	0.002049
T50	T51	1400	Al-500 kcmil	0.0647	0.0643	30.1224	0.0054	0.0054	0.000359
T51	T52	1400	Al-500 kcmil	0.0647	0.0643	30.1224	0.0054	0.0054	0.000359
T52	T53	1400	Al-500 kcmil	0.0647	0.0643	30.1224	0.0054	0.0054	0.000359
T53	T54	1400	Al-500 kcmil	0.0647	0.0643	30.1224	0.0054	0.0054	0.000359
T54	T55	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T55	T56	8000	Al-4/0 AWG	0.8272	0.4160	128.1760	0.0695	0.0350	0.001526
T56	T57	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T57	T58	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T58	T59	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T59	T60	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T60	T61	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T61	T62	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
Sub	JB41	25000	Al-1000 kcmil XB	0.5475	1.0675	676.1500	0.0460	0.0897	0.008048
JB41	T63	8000	Al-4/0 AWG	0.8272	0.4160	128.1760	0.0695	0.0350	0.001526
T63	T64	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T64	T65	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T65	T66	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T66	T67	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T67	T68	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T68	T69	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB41	JB42	8000	Al-500 kcmil	0.3696	0.3672	172.1280	0.0311	0.0309	0.002049
JB42	T70	100	Al-4/0 AWG	0.0103	0.0052	1.6022	0.0009	0.0004	0.000019
T70	T71	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T71	T72	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T72	T73	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB42	T74	10000	Al-4/0 AWG	1.0340	0.5200	160.2200	0.0869	0.0437	0.001907
T74	T75	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267

Table A1-1: 35kV cable impedances used in test system(continued).

From Bus Name	To Bus Name	Length (ft)	Cable Type	R1 (Ohms)	X1 (Ohms)	B1 (Micro Siemens)	R1 (pu)	X1 (pu)	B1 (pu)
T75	T76	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T76	JB43	3000	Al-4/0 AWG	0.3102	0.1560	48.0660	0.0261	0.0131	0.000572
JB43	T77	100	Al-4/0 AWG	0.0103	0.0052	1.6022	0.0009	0.0004	0.000019
T77	T78	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T78	T79	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB43	T80	3000	Al-4/0 AWG	0.3102	0.1560	48.0660	0.0261	0.0131	0.000572
T80	T81	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
Sub	JB51	10000	Al-1000 kcmil XB	0.2190	0.4270	270.4600	0.0184	0.0359	0.003219
JB51	T82	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T82	T83	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB51	JB52	10000	Al-1000 kcmil	0.2520	0.4220	270.4600	0.0212	0.0355	0.003219
JB52	T84	100	Al-4/0 AWG	0.0103	0.0052	1.6022	0.0009	0.0004	0.000019
T84	T85	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T85	T86	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T86	T87	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T87	T88	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB52	JB53	8000	Al-500 kcmil	0.3696	0.3672	172.1280	0.0311	0.0309	0.002049
JB53	T89	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T89	T90	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T90	T91	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T91	T92	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T92	T93	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
JB53	T94	100	Al-4/0 AWG	0.0103	0.0052	1.6022	0.0009	0.0004	0.000019
T94	T95	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T95	T96	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T96	T97	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T97	T98	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T98	T99	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267
T99	T100	1400	Al-4/0 AWG	0.1448	0.0728	22.4308	0.0122	0.0061	0.000267

Appendix 2 Case Study Results for "Window" Scenario

Table A2-1: Case study results for "window" scenario.

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (Optimal Method) (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 1	0.950	150	-4.1	11.3	50	565
Case 2	0.975	150	-4.1	9.9	150	1486
Case 3	1.000	150	-4.1	8.7	300	2613
Case 4	1.025	150	-4.0	7.7	300	2312
Case 5	1.050	150	-3.8	6.8	300	2048
Case 6	0.950	120	-3.2	5.2	75	389
Case 7	0.975	120	-3.2	4.6	175	796
Case 8	1.000	120	-3.2	4.0	375	1517
Case 9	1.025	120	-3.2	3.6	375	1353
Case 10	1.050	120	-3.2	3.2	300	964
Case 11	0.950	90	-2.4	2.0	100	199
Case 12	0.975	90	-2.4	1.8	200	362
Case 13	1.000	90	-2.4	1.7	400	666
Case 14	1.025	90	-2.5	1.5	450	683
Case 15	1.050	90	-2.5	1.4	250	340
Case 16	0.950	60	-1.8	0.7	125	90
Case 17	0.975	60	-1.8	0.7	250	166
Case 18	1.000	60	-1.9	0.7	500	334
Case 19	1.025	60	-1.9	0.6	525	338
Case 20	1.050	60	-2.0	0.6	200	125
Case 21	0.950	30	-1.4	0.4	175	67
Case 22	0.975	30	-1.4	0.4	300	110
Case 23	1.000	30	-1.5	0.4	625	257
Case 24	1.025	30	-1.6	0.4	600	268
Case 25	1.050	30	-1.6	0.4	300	131
Case 26	0.950	0	0.0	0.1	200	22
Case 27	0.975	0	0.0	0.1	250	20
Case 28	1.000	0	0.0	0.1	450	40
Case 29	1.025	0	0.0	0.1	350	34
Case 30	1.050	0	0.0	0.1	110	11
				Totals:	8760	18308

Appendix 3 Case Study Results for the "Rectangular" Scenario

Table A3-1: Cases study results for "Rectangular" scenario.

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 1	0.950	150	47.9	0.0	20	-1
Case 2	0.950	150	33.4	127.0	10	1270
Case 3	0.950	150	0.0	31.9	0	0
Case 4	0.950	150	-33.4	3.7	0	0
Case 5	0.950	150	-48.1	9.7	0	0
Case 6	0.975	150	48.1	21.8	40	873
Case 7	0.975	150	33.4	121.8	20	2435
Case 8	0.975	150	0.0	28.9	10	289
Case 9	0.975	150	-33.4	4.5	0	0
Case 10	0.975	150	-48.1	16.4	0	0
Case 11	1.000	150	48.1	12.7	100	1271
Case 12	1.000	150	33.4	116.4	75	8729
Case 13	1.000	150	0.0	26.1	50	1304
Case 14	1.000	150	-33.4	4.0	40	159
Case 15	1.000	150	-48.1	18.0	10	180
Case 16	1.025	150	36.5	-115.9	100	-11586
Case 17	1.025	150	33.4	0.5	100	47
Case 18	1.025	150	0.0	23.5	250	5881
Case 19	1.025	150	-33.4	4.8	100	480
Case 20	1.025	150	-48.1	17.6	50	880
Case 21	1.050	150	19.3	-304.6	0	0
Case 22	1.050	150	19.3	-304.6	0	0
Case 23	1.050	150	0.0	21.2	25	529
Case 24	1.050	150	-33.4	5.4	50	272
Case 25	1.050	150	-48.1	18.9	50	944
Case 26	0.950	120	48.1	149.5	20	2990
Case 27	0.950	120	33.4	106.6	10	1066
Case 28	0.950	120	0.0	16.1	0	0
Case 29	0.950	120	-33.4	9.2	0	0
Case 30	0.950	120	-43.0	-3.6	0	0
Case 31	0.975	120	48.1	146.7	100	14675
Case 32	0.975	120	33.4	102.3	30	3068
Case 33	0.975	120	0.0	14.2	10	142
Case 34	0.975	120	-33.4	9.2	0	0

Table A3-1: Cases study results for "Rectangular" scenario (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 35	0.975	120	-48.1	28.3	0	0
Case 36	1.000	120	48.1	143.7	120	17246
Case 37	1.000	120	33.4	97.5	80	7801
Case 38	1.000	120	0.0	12.5	75	935
Case 39	1.000	120	-33.4	10.1	50	506
Case 40	1.000	120	-48.1	27.5	15	413
Case 41	1.025	120	45.8	-10.0	120	-1204
Case 42	1.025	120	33.4	93.4	135	12615
Case 43	1.025	120	0.0	10.8	200	2165
Case 44	1.025	120	-33.4	10.5	80	840
Case 45	1.025	120	-48.1	26.2	40	1050
Case 46	1.050	120	28.5	-205.1	0	0
Case 47	1.050	120	28.5	-205.1	15	-3076
Case 48	1.050	120	0.0	9.3	50	463
Case 49	1.050	120	-33.4	10.3	100	1031
Case 50	1.050	120	-48.1	26.2	50	1308
Case 51	0.950	90	48.1	139.8	50	6992
Case 52	0.950	90	33.4	88.4	15	1326
Case 53	0.950	90	0.0	5.0	0	0
Case 54	0.950	90	-33.4	4.8	0	0
Case 55	0.950	90	-34.3	-1.7	0	0
Case 56	0.975	90	48.1	136.4	110	15001
Case 57	0.975	90	33.4	85.9	50	4293
Case 58	0.975	90	0.0	3.8	10	38
Case 59	0.975	90	-33.4	15.9	0	0
Case 60	0.975	90	-48.1	30.9	0	0
Case 61	1.000	90	48.1	132.3	120	15879
Case 62	1.000	90	33.4	82.1	100	8205
Case 63	1.000	90	0.0	2.7	85	231
Case 64	1.000	90	-33.4	15.2	65	990
Case 65	1.000	90	-48.1	36.6	30	1099
Case 66	1.025	90	48.1	125.2	150	18776
Case 67	1.025	90	33.4	79.1	150	11868
Case 68	1.025	90	0.0	1.7	150	260
Case 69	1.025	90	-33.4	15.1	75	1133
Case 70	1.025	90	-48.1	36.2	30	1087
Case 71	1.050	90	36.3	-203.0	20	-4059

Table A3-1: Cases study results for “Rectangular” scenario (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 72	1.050	90	33.4	7.0	35	244
Case 73	1.050	90	0.0	0.7	45	33
Case 74	1.050	90	-33.4	15.4	70	1075
Case 75	1.050	90	-48.1	34.7	40	1388
Case 76	0.950	60	48.1	128.7	60	7724
Case 77	0.950	60	33.4	77.1	20	1541
Case 78	0.950	60	0.0	0.2	0	0
Case 79	0.950	60	-27.1	-1.8	0	0
Case 80	0.950	60	-27.1	-1.8	0	0
Case 81	0.975	60	48.1	125.3	120	15039
Case 82	0.975	60	33.4	74.0	100	7396
Case 83	0.975	60	0.0	0.1	15	2
Case 84	0.975	60	-33.4	21.5	0	0
Case 85	0.975	60	-44.6	-0.6	0	0
Case 86	1.000	60	48.1	121.7	130	15827
Case 87	1.000	60	33.4	71.9	110	7910
Case 88	1.000	60	0.0	0.1	90	13
Case 89	1.000	60	-33.4	21.8	75	1639
Case 90	1.000	60	-48.1	45.2	40	1806
Case 91	1.025	60	48.1	118.1	100	11806
Case 92	1.025	60	33.4	69.8	200	13962
Case 93	1.025	60	0.0	0.1	200	22
Case 94	1.025	60	-33.4	21.0	100	2104
Case 95	1.025	60	-48.1	43.7	40	1747
Case 96	1.050	60	42.8	-145.4	20	-2908
Case 97	1.050	60	33.4	67.7	30	2031
Case 98	1.050	60	0.0	0.1	60	6
Case 99	1.050	60	-33.4	20.4	60	1227
Case 100	1.050	60	-48.1	42.7	30	1280
Case 101	0.950	30	48.1	121.5	80	9719
Case 102	0.950	30	33.4	70.4	10	704
Case 103	0.950	30	0.0	0.1	0	0
Case 104	0.950	30	-21.2	-0.6	0	0
Case 105	0.950	30	-21.2	-0.6	0	0
Case 106	0.975	30	48.1	118.5	150	17778
Case 107	0.975	30	33.4	68.8	125	8596
Case 108	0.975	30	0.0	0.0	45	2

Table A3-1: Cases study results for “Rectangular” scenario (continued).

Case 109	0.975	30	-33.4	26.1	0	0
Case 110	0.975	30	-38.8	0.8	0	0
Case 111	1.000	30	48.1	115.5	200	23108
Case 112	1.000	30	33.4	66.2	200	13234
Case 113	1.000	30	0.0	0.1	200	14
Case 114	1.000	30	-33.4	26.0	75	1952
Case 115	1.000	30	-48.1	51.6	25	1290
Case 116	1.025	30	48.1	112.6	180	20269
Case 117	1.025	30	33.4	64.7	200	12938
Case 118	1.025	30	0.0	0.1	220	21
Case 119	1.025	30	-33.4	24.5	90	2207
Case 120	1.025	30	-48.1	49.0	30	1471
Case 121	1.050	30	48.0	-14.2	0	0
Case 122	1.050	30	33.4	63.2	10	632
Case 123	1.050	30	0.0	0.1	40	3
Case 124	1.050	30	-33.4	23.2	70	1622
Case 125	1.050	30	-48.1	46.8	50	2339
Case 126	0.950	0	0.0	0.1	100	7
Case 127	0.975	0	0.0	0.1	300	24
Case 128	1.000	0	0.0	0.1	400	36
Case 129	1.025	0	0.0	0.1	440	43
Case 130	1.050	0	0.0	0.1	120	12
				Totals:	8760	372045

Appendix 4 Case Study Results for the "Rectangular" Scenario with Extended Voltage Range

Table A4-1: Cases study results for "Rectangular" scenario with extended voltage range.

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 1	0.950	150	48.1	166.3	20	3325
Case 2	0.950	150	33.4	197.2	10	1972
Case 3	0.950	150	0.0	8.6	0	0
Case 4	0.950	150	-33.4	216.8	0	0
Case 5	0.950	150	-48.1	145.8	0	0
Case 6	0.975	150	48.1	156.8	40	6272
Case 7	0.975	150	33.4	187.3	20	3746
Case 8	0.975	150	0.0	7.3	10	73
Case 9	0.975	150	-33.4	211.2	0	0
Case 10	0.975	150	-48.1	354.0	0	0
Case 11	1.000	150	48.1	147.5	100	14751
Case 12	1.000	150	33.4	178.6	75	13391
Case 13	1.000	150	0.0	6.3	50	314
Case 14	1.000	150	-33.4	204.1	40	8165
Case 15	1.000	150	-48.1	347.3	10	3473
Case 16	1.025	150	48.1	124.3	100	12427
Case 17	1.025	150	33.4	154.3	100	15430
Case 18	1.025	150	0.0	5.5	250	1366
Case 19	1.025	150	-33.4	198.2	100	19820
Case 20	1.025	150	-48.1	342.3	50	17113
Case 21	1.050	150	48.1	-230.0	0	0
Case 22	1.050	150	33.4	38.4	0	0
Case 23	1.050	150	0.0	4.7	25	118
Case 24	1.050	150	-33.4	191.9	50	9596
Case 25	1.050	150	-48.1	335.1	50	16753
Case 26	0.950	120	48.1	348.0	20	6960
Case 27	0.950	120	33.4	192.6	10	1926
Case 28	0.950	120	0.0	3.5	0	0
Case 29	0.950	120	-33.4	216.9	0	0
Case 30	0.950	120	-48.1	148.5	0	0
Case 31	0.975	120	48.1	339.4	100	33936

Table A4-1: Cases study results for "Rectangular" scenario with extended voltage range (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 32	0.975	120	33.4	184.2	30	5527
Case 33	0.975	120	0.0	3.0	10	30
Case 34	0.975	120	-33.4	209.1	0	0
Case 35	0.975	120	-48.1	359.9	0	0
Case 36	1.000	120	48.1	328.3	120	39394
Case 37	1.000	120	33.4	176.2	80	14096
Case 38	1.000	120	0.0	2.6	75	191
Case 39	1.000	120	-33.4	203.6	50	10181
Case 40	1.000	120	-48.1	350.9	15	5264
Case 41	1.025	120	48.1	282.2	120	33864
Case 42	1.025	120	33.4	167.5	135	22619
Case 43	1.025	120	0.0	2.2	200	436
Case 44	1.025	120	-33.4	197.4	80	15792
Case 45	1.025	120	-48.1	347.1	40	13883
Case 46	1.050	120	48.1	91.1	0	0
Case 47	1.050	120	33.4	132.7	15	1990
Case 48	1.050	120	0.0	1.8	50	92
Case 49	1.050	120	-33.4	190.5	100	19047
Case 50	1.050	120	-48.1	338.5	50	16925
Case 51	0.950	90	48.1	345.0	50	17249
Case 52	0.950	90	33.4	190.2	15	2853
Case 53	0.950	90	0.0	1.0	0	0
Case 54	0.950	90	-33.4	73.4	0	0
Case 55	0.950	90	-48.1	4.6	0	0
Case 56	0.975	90	48.1	336.4	110	37008
Case 57	0.975	90	33.4	183.0	50	9151
Case 58	0.975	90	0.0	0.9	10	9
Case 59	0.975	90	-33.4	210.2	0	0
Case 60	0.975	90	-48.1	364.8	0	0
Case 61	1.000	90	48.1	327.3	120	39271
Case 62	1.000	90	33.4	175.3	100	17533
Case 63	1.000	90	0.0	0.8	85	66
Case 64	1.000	90	-33.4	203.3	65	13216
Case 65	1.000	90	-48.1	357.5	30	10724
Case 66	1.025	90	48.1	317.5	150	47632

Table A4-1: Cases study results for "Rectangular" scenario with extended voltage range (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 67	1.025	90	33.4	167.3	150	25088
Case 68	1.025	90	0.0	0.7	150	98
Case 69	1.025	90	-33.4	198.0	75	14852
Case 70	1.025	90	-48.1	350.8	30	10524
Case 71	1.050	90	48.1	120.0	20	2399
Case 72	1.050	90	33.4	158.8	35	5559
Case 73	1.050	90	0.0	0.5	45	23
Case 74	1.050	90	-33.4	190.4	70	13327
Case 75	1.050	90	-48.1	342.8	40	13711
Case 76	0.950	60	48.1	345.3	60	20718
Case 77	0.950	60	33.4	191.2	20	3825
Case 78	0.950	60	0.0	0.2	0	0
Case 79	0.950	60	-33.4	74.7	0	0
Case 80	0.950	60	-48.1	7.5	0	0
Case 81	0.975	60	48.1	336.7	120	40406
Case 82	0.975	60	33.4	184.0	100	18401
Case 83	0.975	60	0.0	0.1	15	2
Case 84	0.975	60	-33.4	212.0	0	0
Case 85	0.975	60	-48.1	151.9	0	0
Case 86	1.000	60	48.1	327.8	130	42610
Case 87	1.000	60	33.4	175.5	110	19301
Case 88	1.000	60	0.0	0.1	90	13
Case 89	1.000	60	-33.4	206.1	75	15458
Case 90	1.000	60	-48.1	363.4	40	14536
Case 91	1.025	60	48.1	318.5	100	31854
Case 92	1.025	60	33.4	167.7	200	33548
Case 93	1.025	60	0.0	0.1	200	22
Case 94	1.025	60	-33.4	198.9	100	19894
Case 95	1.025	60	-48.1	355.7	40	14229
Case 96	1.050	60	48.1	121.3	20	2426
Case 97	1.050	60	33.4	159.8	30	4794
Case 98	1.050	60	0.0	0.1	60	6
Case 99	1.050	60	-33.4	191.8	60	11510
Case 100	1.050	60	-48.1	348.3	30	10449
Case 101	0.950	30	48.1	346.9	80	27752

Table A4-1: Cases study results for "Rectangular" scenario with extended voltage range (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 102	0.950	30	33.4	192.9	10	1929
Case 103	0.950	30	0.0	0.1	0	0
Case 104	0.950	30	-33.4	76.0	0	0
Case 105	0.950	30	-48.1	1.3	0	0
Case 106	0.975	30	48.1	338.4	150	50756
Case 107	0.975	30	33.4	185.6	125	23203
Case 108	0.975	30	0.0	0.0	45	2
Case 109	0.975	30	-33.4	214.7	0	0
Case 110	0.975	30	-48.1	156.0	0	0
Case 111	1.000	30	48.1	329.7	200	65933
Case 112	1.000	30	33.4	177.2	200	35442
Case 113	1.000	30	0.0	0.1	200	14
Case 114	1.000	30	-33.4	207.0	75	15524
Case 115	1.000	30	-48.1	369.5	25	9237
Case 116	1.025	30	48.1	320.8	180	57747
Case 117	1.025	30	33.4	169.7	200	33948
Case 118	1.025	30	0.0	0.1	220	21
Case 119	1.025	30	-33.4	200.5	90	18049
Case 120	1.025	30	-48.1	360.7	30	10822
Case 121	1.050	30	48.1	311.8	0	0
Case 122	1.050	30	33.4	162.1	10	1621
Case 123	1.050	30	0.0	0.1	40	3
Case 124	1.050	30	-33.4	192.7	70	13490
Case 125	1.050	30	-48.1	352.1	50	17605
Case 126	0.950	0	0.0	0.1	100	7
Case 127	0.975	0	0.0	0.1	300	24
Case 128	1.000	0	0.0	0.1	400	36
Case 129	1.025	0	0.0	0.1	440	43
Case 130	1.050	0	0.0	0.1	120	12
				Totals:	8760	1357770

Appendix 5 Case Study Results for the "Triangular" Scenario

Table A5-1: Case study results for "Triangular" scenario.

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 1	0.950	150	47.9	0.0	20	-1
Case 2	0.950	150	33.4	127.0	10	1270
Case 3	0.950	150	0.0	31.9	0	0
Case 4	0.950	150	-33.4	3.7	0	0
Case 5	0.950	150	-48.1	10.3	0	0
Case 6	0.975	150	48.1	21.8	40	873
Case 7	0.975	150	33.4	121.8	20	2435
Case 8	0.975	150	0.0	28.9	10	289
Case 9	0.975	150	-33.4	4.5	0	0
Case 10	0.975	150	-48.1	16.4	0	0
Case 11	1.000	150	48.1	11.9	100	1188
Case 12	1.000	150	33.4	116.4	75	8729
Case 13	1.000	150	0.0	26.1	50	1304
Case 14	1.000	150	-33.4	4.0	40	159
Case 15	1.000	150	-48.1	18.0	10	180
Case 16	1.025	150	36.5	-115.9	100	-11586
Case 17	1.025	150	33.4	-5.3	100	-534
Case 18	1.025	150	0.0	23.5	250	5881
Case 19	1.025	150	-33.4	4.8	100	480
Case 20	1.025	150	-48.1	17.6	50	880
Case 21	1.050	150	19.3	-304.2	0	0
Case 22	1.050	150	19.3	-304.2	0	0
Case 23	1.050	150	0.0	21.2	25	529
Case 24	1.050	150	-33.4	5.4	50	272
Case 25	1.050	150	-48.1	18.9	50	944
Case 26	0.950	120	38.5	123.2	25	3079
Case 27	0.950	120	26.7	84.5	5	423
Case 28	0.950	120	0.0	16.0	0	0
Case 29	0.950	120	-26.7	3.9	0	0
Case 30	0.950	120	-38.5	11.7	0	0
Case 31	0.975	120	38.5	118.9	115	13673
Case 32	0.975	120	26.7	89.1	15	1337
Case 33	0.975	120	0.0	14.2	10	142
Case 34	0.975	120	-26.7	4.3	0	0
Case 35	0.975	120	-38.5	14.5	0	0

Table A5-1: Case study results for "Triangular" scenario (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 36	1.000	120	38.5	114.0	160	18241
Case 37	1.000	120	26.7	77.1	40	3083
Case 38	1.000	120	0.0	12.5	75	935
Case 39	1.000	120	-26.7	4.3	30	130
Case 40	1.000	120	-38.5	15.1	35	527
Case 41	1.025	120	38.5	108.3	180	19500
Case 42	1.025	120	26.7	73.4	75	5505
Case 43	1.025	120	0.0	10.8	200	2165
Case 44	1.025	120	-26.7	5.0	80	399
Case 45	1.025	120	-38.5	15.0	40	602
Case 46	1.050	120	28.5	-255.4	0	0
Case 47	1.050	120	26.7	-84.2	15	-1263
Case 48	1.050	120	0.0	9.3	50	463
Case 49	1.050	120	-26.7	5.2	100	517
Case 50	1.050	120	-38.5	14.5	50	723
Case 51	0.950	90	28.9	28.8	50	1438
Case 52	0.950	90	20.0	16.4	15	246
Case 53	0.950	90	0.0	1.0	0	0
Case 54	0.950	90	-20.0	4.4	0	0
Case 55	0.950	90	-28.9	10.3	0	0
Case 56	0.975	90	28.9	26.4	110	2902
Case 57	0.975	90	20.0	15.3	50	763
Case 58	0.975	90	0.0	0.9	10	9
Case 59	0.975	90	-20.0	4.3	0	0
Case 60	0.975	90	-28.9	11.2	0	0
Case 61	1.000	90	28.9	24.7	120	2970
Case 62	1.000	90	20.0	14.0	100	1405
Case 63	1.000	90	0.0	0.8	85	66
Case 64	1.000	90	-20.0	4.5	35	157
Case 65	1.000	90	-28.9	11.0	60	658
Case 66	1.025	90	28.9	23.8	150	3570
Case 67	1.025	90	20.0	12.7	150	1912
Case 68	1.025	90	0.0	0.7	150	98
Case 69	1.025	90	-20.0	4.2	50	208
Case 70	1.025	90	-28.9	11.1	55	613
Case 71	1.050	90	28.9	7.4	20	149
Case 72	1.050	90	20.0	12.0	35	418

Table A5-1: Case study results for "Triangular" scenario (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 73	1.050	90	0.0	0.6	45	25
Case 74	1.050	90	-20.0	4.1	35	143
Case 75	1.050	90	-28.9	10.6	75	792
Case 76	0.950	60	19.2	36.7	80	2936
Case 77	0.950	60	13.4	23.0	10	230
Case 78	0.950	60	0.0	0.2	0	0
Case 79	0.950	60	-13.4	3.0	0	0
Case 80	0.950	60	-19.2	6.7	0	0
Case 81	0.975	60	19.2	35.2	170	5981
Case 82	0.975	60	13.4	21.7	50	1086
Case 83	0.975	60	0.0	0.1	15	2
Case 84	0.975	60	-13.4	2.5	0	0
Case 85	0.975	60	-19.2	6.7	0	0
Case 86	1.000	60	19.2	33.7	190	6397
Case 87	1.000	60	13.4	20.5	50	1025
Case 88	1.000	60	0.0	0.1	90	13
Case 89	1.000	60	-13.4	2.8	40	111
Case 90	1.000	60	-19.2	6.0	75	453
Case 91	1.025	60	19.2	32.7	200	6546
Case 92	1.025	60	13.4	19.7	100	1967
Case 93	1.025	60	0.0	0.1	200	22
Case 94	1.025	60	-13.4	2.5	40	101
Case 95	1.025	60	-19.2	6.2	90	560
Case 96	1.050	60	19.2	31.2	35	1093
Case 97	1.050	60	13.4	18.8	15	282
Case 98	1.050	60	0.0	0.1	60	6
Case 99	1.050	60	-13.4	2.3	30	70
Case 100	1.050	60	-19.2	5.8	60	346
Case 101	0.950	30	9.6	9.8	80	784
Case 102	0.950	30	6.7	4.5	10	45
Case 103	0.950	30	0.0	0.1	0	0
Case 104	0.950	30	-6.7	1.1	0	0
Case 105	0.950	30	-9.6	2.4	0	0
Case 106	0.975	30	9.6	9.0	225	2033
Case 107	0.975	30	6.7	3.8	50	190
Case 108	0.975	30	0.0	0.0	45	2
Case 109	0.975	30	-6.7	1.3	0	0

Table A5-1: Case study results for "Triangular" scenario (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 110	0.975	30	-9.6	2.1	0	0
Case 111	1.000	30	9.6	8.6	300	2576
Case 112	1.000	30	6.7	3.3	100	334
Case 113	1.000	30	0.0	0.1	200	14
Case 114	1.000	30	-6.7	1.1	35	38
Case 115	1.000	30	-9.6	2.2	65	142
Case 116	1.025	30	9.6	7.9	280	2201
Case 117	1.025	30	6.7	2.7	100	271
Case 118	1.025	30	0.0	0.0	220	11
Case 119	1.025	30	-6.7	1.2	45	53
Case 120	1.025	30	-9.6	2.3	75	171
Case 121	1.050	30	9.6	7.2	5	36
Case 122	1.050	30	6.7	2.1	5	10
Case 123	1.050	30	0.0	0.1	40	3
Case 124	1.050	30	-6.7	1.0	35	34
Case 125	1.050	30	-9.6	2.0	85	169
Case 126	0.950	0	0.0	0.1	100	7
Case 127	0.975	0	0.0	0.1	300	24
Case 128	1.000	0	0.0	0.1	400	36
Case 129	1.025	0	0.0	0.1	440	43
Case 130	1.050	0	0.0	0.1	120	12
				Totals:	8760	140474

Appendix 6 Case Study Results for the “Triangular” Scenario with Extended Voltage Range

Table A6-1: Case study results for “Triangular” scenario with extended voltage range

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 1	0.950	150	48.1	166.3	20	3325
Case 2	0.950	150	33.4	197.2	10	1972
Case 3	0.950	150	0.0	8.5	0	0
Case 4	0.950	150	-33.4	3.7	0	0
Case 5	0.950	150	-48.1	10.9	0	0
Case 6	0.975	150	48.1	156.8	40	6272
Case 7	0.975	150	33.4	187.3	20	3746
Case 8	0.975	150	0.0	7.3	10	73
Case 9	0.975	150	-33.4	4.5	0	0
Case 10	0.975	150	-48.1	16.4	0	0
Case 11	1.000	150	48.1	147.5	100	14752
Case 12	1.000	150	33.4	177.6	75	13317
Case 13	1.000	150	0.0	6.3	50	314
Case 14	1.000	150	-33.4	4.0	40	159
Case 15	1.000	150	-48.1	18.0	10	180
Case 16	1.025	150	48.1	123.9	100	12388
Case 17	1.025	150	33.4	154.3	100	15430
Case 18	1.025	150	0.0	5.4	250	1352
Case 19	1.025	150	-33.4	4.8	100	480
Case 20	1.025	150	-48.1	17.6	50	880
Case 21	1.050	150	48.1	-230.3	0	0
Case 22	1.050	150	33.4	38.2	0	0
Case 23	1.050	150	0.0	4.7	25	116
Case 24	1.050	150	-33.4	5.4	50	272
Case 25	1.050	150	-48.1	18.9	50	944
Case 26	0.950	120	38.5	246.2	25	6156
Case 27	0.950	120	26.7	124.4	5	622
Case 28	0.950	120	0.0	3.5	0	0
Case 29	0.950	120	-26.7	5.0	0	0
Case 30	0.950	120	-38.5	11.7	0	0
Case 31	0.975	120	38.5	236.4	115	27190

Table A6-1: Case study results for "Triangular" scenario with extended voltage range (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 32	0.975	120	26.7	116.3	15	1745
Case 33	0.975	120	0.0	3.0	10	30
Case 34	0.975	120	-26.7	4.3	0	0
Case 35	0.975	120	-38.5	14.5	0	0
Case 36	1.000	120	38.5	227.1	160	36342
Case 37	1.000	120	26.7	108.5	40	4342
Case 38	1.000	120	0.0	2.6	75	191
Case 39	1.000	120	-26.7	4.3	30	130
Case 40	1.000	120	-38.5	15.1	35	527
Case 41	1.025	120	38.5	218.3	180	39297
Case 42	1.025	120	26.7	100.3	75	7522
Case 43	1.025	120	0.0	2.2	200	436
Case 44	1.025	120	-26.7	5.0	80	399
Case 45	1.025	120	-38.5	15.0	40	602
Case 46	1.050	120	38.5	70.2	0	0
Case 47	1.050	120	26.7	84.2	15	1263
Case 48	1.050	120	0.0	1.9	50	94
Case 49	1.050	120	-26.7	5.2	100	517
Case 50	1.050	120	-38.5	15.9	50	793
Case 51	0.950	90	28.9	145.3	50	7265
Case 52	0.950	90	20.0	63.8	15	957
Case 53	0.950	90	0.0	1.0	0	0
Case 54	0.950	90	-20.0	4.4	0	0
Case 55	0.950	90	-28.9	10.3	0	0
Case 56	0.975	90	28.9	138.2	110	15200
Case 57	0.975	90	20.0	61.3	50	3063
Case 58	0.975	90	0.0	0.9	10	9
Case 59	0.975	90	-20.0	4.3	0	0
Case 60	0.975	90	-28.9	11.2	0	0
Case 61	1.000	90	28.9	130.6	120	15675
Case 62	1.000	90	20.0	58.5	100	5854
Case 63	1.000	90	0.0	0.8	85	66
Case 64	1.000	90	-20.0	4.5	35	157
Case 65	1.000	90	-28.9	11.0	60	658
Case 66	1.025	90	28.9	122.7	150	18408
Case 67	1.025	90	20.0	55.7	150	8354

Table A6-1: Case study results for "Triangular" scenario with extended voltage range (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 68	1.025	90	0.0	0.7	150	98
Case 69	1.025	90	-20.0	4.2	50	208
Case 70	1.025	90	-28.9	11.1	55	613
Case 71	1.050	90	28.9	114.5	20	2290
Case 72	1.050	90	20.0	53.3	35	1865
Case 73	1.050	90	0.0	0.6	45	25
Case 74	1.050	90	-20.0	4.1	35	143
Case 75	1.050	90	-28.9	10.6	75	792
Case 76	0.950	60	19.2	58.4	80	4669
Case 77	0.950	60	13.4	28.6	10	286
Case 78	0.950	60	0.0	0.2	0	0
Case 79	0.950	60	-13.4	3.0	0	0
Case 80	0.950	60	-13.4	41.9	0	0
Case 81	0.975	60	19.2	56.0	170	9514
Case 82	0.975	60	13.4	26.4	50	1322
Case 83	0.975	60	0.0	0.1	15	2
Case 84	0.975	60	-13.4	3.1	0	0
Case 85	0.975	60	-13.4	40.2	0	0
Case 86	1.000	60	19.2	53.5	190	10166
Case 87	1.000	60	13.4	24.2	50	1212
Case 88	1.000	60	0.0	0.1	90	13
Case 89	1.000	60	-13.4	2.8	40	111
Case 90	1.000	60	-13.4	38.0	75	2847
Case 91	1.025	60	19.2	51.0	200	10198
Case 92	1.025	60	13.4	22.4	100	2237
Case 93	1.025	60	0.0	0.1	200	22
Case 94	1.025	60	-13.4	2.5	40	101
Case 95	1.025	60	-13.4	36.7	90	3304
Case 96	1.050	60	19.2	49.0	35	1714
Case 97	1.050	60	13.4	20.4	15	307
Case 98	1.050	60	0.0	0.1	60	6
Case 99	1.050	60	-13.4	2.8	30	85
Case 100	1.050	60	-13.4	34.9	60	2095
Case 101	0.950	30	9.6	2.3	80	185
Case 102	0.950	30	6.7	1.2	10	12
Case 103	0.950	30	0.0	0.1	0	0

Table A6-1: Case study results for "Triangular" scenario with extended voltage range (continued).

	POI Voltage (pu)	Real Power Generation (MW)	Reactive Power Generation (MVAr)	Savings (kW)	Frequency (hrs/year)	Savings per Year (kWhr)
Case 104	0.950	30	-6.7	1.1	0	0
Case 105	0.950	30	-9.6	2.4	0	0
Case 106	0.975	30	9.6	2.1	225	461
Case 107	0.975	30	6.7	1.0	50	52
Case 108	0.975	30	0.0	0.1	45	4
Case 109	0.975	30	-6.7	1.0	0	0
Case 110	0.975	30	-9.6	2.1	0	0
Case 111	1.000	30	9.6	2.1	300	628
Case 112	1.000	30	6.7	0.9	100	90
Case 113	1.000	30	0.0	0.1	200	14
Case 114	1.000	30	-6.7	1.1	35	38
Case 115	1.000	30	-9.6	2.2	65	142
Case 116	1.025	30	9.6	1.9	280	522
Case 117	1.025	30	6.7	0.9	100	94
Case 118	1.025	30	0.0	0.0	220	11
Case 119	1.025	30	-6.7	1.2	45	53
Case 120	1.025	30	-9.6	2.3	75	171
Case 121	1.050	30	9.6	1.7	5	8
Case 122	1.050	30	6.7	0.8	5	4
Case 123	1.050	30	0.0	0.1	40	3
Case 124	1.050	30	-6.7	1.0	35	34
Case 125	1.050	30	-9.6	2.0	85	169
Case 126	0.950	0	0.0	0.1	100	11
Case 127	0.975	0	0.0	0.1	300	24
Case 128	1.000	0	0.0	0.1	400	36
Case 129	1.025	0	0.0	0.1	440	43
Case 130	1.050	0	0.0	0.1	120	12
				Totals:	8760	338897